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and Steven E. Belsley ~

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National Aeronautics and  
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16. Abstract <p>The progress of the civil air transport industry in the United States has been examined in the light of a proposal of Enos who, after examining the growth of the petroleum industry, has divided that phenomenon into two phases, the alpha and the beta; that is, the invention, first development and production, and the improvement phase.</p> <p>The industry did indeed develop along similar lines with the technological progress coming in waves; each wave encompassing several new technological advances while retaining the best of the old ones. At the same time the productivity of the transport aircraft as expressed by the product (<math>V_{CX}A_S</math>) of the aircraft velocity (<math>V_C</math>) and the passenger capacity (<math>A_S</math>) increased sufficiently to allow the direct operating cost in cents per passenger mile to continually decrease with each successive aircraft development.</p>					
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IN THE AIR TRANSPORT INDUSTRY

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## INTRODUCTION

When most people think of the technological innovations of the 20th Century, they think of such things as radio, television, antibiotics, birth-control pills, and synthetic materials, synthetic fibres, automobiles, helicopters, jet transports, airplanes, atom bomb, space exploration, computers. This is perfectly proper. The 20th Century has witnessed numerous spectacular innovations, and it is perfectly appropriate that technological innovation should be symbolized in peoples' minds by dramatic breakthroughs such as these.

However, if we shift our thinking to other levels, the story becomes much more complicated. For the social process out of which such innovations eventually emerged was usually much less dramatic, consisting of innumerable steps, most of them typically very small, in the fashioning of a new device or technique. Moreover, such technological innovation itself has a long "pre-history," during which time it is subjected to a series of improvements until it becomes practically workable. It also has a long "post-history," during which time the innovation is subjected to a prolonged series of further improvements. Such improvements may include redesigning to economize on materials, substitution of new materials possessing superior performance characteristics, modifications to meet the specialized needs of numerous submarkets or sub-uses, treatment procedures to prolong the life of components, etc. The point is that our mental conceptions offer a still-picture of what is, in reality, a long, drawn out dynamic process.

These points become particularly significant when our concern is not restricted to technological history in the narrow sense but includes the economic consequences of new technologies. For, things which may be of secondary or even of trivial importance for technological history may be the very essence of economic success or failure. Innovations which in technological terms are quite spectacular and compelling may fail to meet elementary

commercial tests and constitute economic failures. Conversely, minor, pedantic improvements in a product or process which may be totally unnewsworthy and, indeed, invisible to all except highly trained specialists, may spell the decisive difference between commercial success or failure. Thus, the economic analysis of a technological innovation may involve a very different focus from what appears in popular or engineering accounts. Even where an innovation involves entirely new concepts, or constitutes a genuine discontinuity, a sharp and dramatic departure from the past, its contribution to the growth of productivity will make itself felt only more slowly, as numerous obstacles are overcome, as many small improvements and modifications are introduced, and as necessary conditions are fulfilled which are essential to the full exploitation of improvements which already exist. Application of technology to users' needs requires a demand (either active or latent) for a service that can be satisfied by a new device or devices. At the time the new device is developed and introduced it must embody those technology advances that enable it to meet the performance requirements and return a profit to both the builder and the user. In addition, increases in the useability of the device can create an increased demand for it, and as more of the devices are manufactured and sold opportunity exists to improve the device to make it even more useable or profitable. When the market becomes large enough, other builders will construct other devices and will use the available pool of technology in a different way to develop a marketable device. Studies of the flow and ebb of industries, especially the petroleum refining industry, has led Enos<sup>1</sup> to offer an explanation of technological progress which divides that phenomenon into two phases, the alpha and the beta. The alpha phase consists of the invention, development and first production plants. The beta phase consists of the improvement of the innovation to improve the economic viability of the device.

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<sup>1</sup>John Enos, "Invention and Innovation in the Petroleum Refining Industry, in The Rate and Direction of Inventive Activity, Princeton University Press, 1962.

This study examines and analyzes the air transport industry from the point of review of the alpha and beta phase concept of Enos to determine if these phases can be applied to this industry and to shed some light on the motivating forces afoot in the industry.

#### GENERAL BACKGROUND

In any industry, the growth of that industry is usually brought about by providing a need not satisfied elsewhere. In the transport industry, this need is speed of movement. Of course, the public is not prepared to pay unlimited amounts for this increase in speed. Indeed, as we will show innovations have been introduced in the air transport industry only when they have been associated with cost reduction or obtaining another desirable characteristic. It has been proven many times that the passenger is willing to pay a premium for this speed. The growth of the air transport industry from its inception in 1926 stimulated by the government by contracting with private concerns to carry the U.S. air mail has been steady and sometimes very rapid (see Fig. 1).<sup>2,3</sup> Because of the original payment schemes for airmail routes of so many dollars per mile of route flown

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<sup>2</sup>Smith, Henry Ladd, Airways; the History of Commerical Aviation in the United States, A. A. Knopf, N. Y., 1942.

<sup>3</sup>Warner, E. P., The Early History of Air Transportation - A Lecture delivered at Norwich University, No. 21, 1937, Maple Press, York (England) 1937.



per trip, there was not a great emphasis on passenger-carrying capability, although this increased as more experience was gained with the flying of the route and provided extra revenue to the operators. Previous passenger-carrying operations were hard put to make ends meet without airmail payments. In addition, the U.S. Government constructed and maintained lighted airways, promoted airfields and provided other services that were very necessary to the operation of aircraft across country on a regular basis. Because of the form of the airmail payment, initially, a rate based on a percentage of the airmail revenue, changed later to a pound rate (up to \$3 per pound for the first 1000 miles plus 30¢ per mile for each extra 100 miles)<sup>1</sup>, the drive to reduce direct operating costs to a minimum was not highly developed; however, safety and reliability of operations were necessary if the airline operators were to make any money at all (by increasing the appeal of passenger service).

In this time period (1922-1930), aircraft developed from single-engine fabric-covered biplanes to trimotor<sup>2,3</sup> and 4-engine high-wing monoplanes of both all-metal and plywood construction, as well as continuing the progression of large biplanes. To further encourage the development and expansion of passenger-carrying air transport systems, the McNary-Watres Act was passed on April 29, 1930, which changed the method of compensation to paying the airline operators for the cargo space available plus extra for passenger-carrying capacity, navigational aids furnished (such as radio), and night-flying capability. In addition, capability of consolidating the present airmail system was granted which resulted, following government pressure, in eliminating small operators and establishment of a trunk line system which basically is in existence today.

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<sup>1</sup>Smith, H. L., Airways, The History of Commercial Aviation in the United States. A. Knopf, N. Y., 1942, Appendix I and II.

<sup>2</sup>Ingles, Douglas J., Tin Goose-The Fabulous Ford Trimotor, Aero Publishers, Inc., Fallbrook, Calif., 1968.

<sup>3</sup>See also Chapt. 4, The Airframe Revolution from the book by John B. Rae, "Climb to Greatness, pp. 58-76, The MIT Press, Cambridge, Mass., 1968.

The stimulus given to the air transport system resulted in the availability of greater revenues and sufficient amounts of capital funds to enable larger and faster aircraft to be considered and acquired, and hence being able to cope with the growth in passenger traffic, both projected and real.

Because of the progress of aeronautical research by NACA and development of powerful radial air-cooled engines for the U.S. Navy by Pratt-Whitney and Curtiss Wright, and the support of all-metal aircraft construction by the Army and Navy and private operators, it was possible to configure aircraft made completely of metal that would operate at much higher speeds and lower costs and could completely change the complexion of the air transport system. The research work of NACA pointed out at this time (1928-1929) the tremendous gain to be had in increasing speed by streamlining (reducing drag) and using the cowled radial engine.<sup>1</sup> This, coupled with a need for safety and reliability in operation, pointed the way to twin-engine low-wing all-metal monoplanes as the most effective solution to the problem of traversing the country from coast-to-coast in less than 24 hours while carrying a reasonable payload (at a direct operating cost less than a Ford trimotor). The first such machine was the Boeing-247<sup>2,3</sup> with a cruising speed of 180 mph carrying a passenger complement of 10, and with the capacity of 1000 pounds of cargo for mail. This machine was developed to enable United Air Transport, Inc., to meet the competition of TWA on the Chicago to West Coast run. TWA having acquired Fokker F-32's (large 30-passenger, 125 mph cruise) to fly the run to augment the Ford and Fokker

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<sup>1</sup>Warner, Ed P., Technical Development and its Effect on Air Transportation - A Lecture delivered at Norwich University, Feb. 23, 1938, Maple Press, York (England) 1938.

<sup>2</sup>Ingles, Douglas J., 747, The Story of the Boeing Super Jet, Aero Publishers, Inc., Fallbrook CA, 1970.

<sup>3</sup>Bowers, Peter M., Boeing Aircraft since 1916, Putnam, London, 2nd Ed., 1968.

trimotors already in hand. Subsequently, all Fokkers were removed from service because of the investigation surrounding a crash on March 31, 1931 in Kansas<sup>1</sup> which killed then-famous Knute Rockne.<sup>2</sup> This placed TWA at a competitive disadvantage and resulted in their request to Douglas for a new aircraft--the DC-1 and DC-2 resulted from this inquiry.

In the above, it is noted that the driving force to cause change was the requirement for increased performance (speed) and load-carrying capacity by the U.S. Post Office put in such a way as to release the competitive drive of the various companies and individuals involved. These companies responded by supporting the development of these new machines which could enhance their income and prestige. It was not a broad marketplace, however.

After the DC-2 was developed and introduced in 1934, progress was spurred by the requirement of the airlines to meet the surge in traffic demand; from this the DST (DC-3) was developed, and this machine dominated the airways for three years. As traffic increased in volume, the airlines funded Douglas to construct a four-engine aircraft. The DC-4E was built and, although not acceptable, did lay the groundwork for a redesign resulting in the DC-4, which was used as the basis for the DC-6/DC-7 series aircraft. At the same time, Boeing used its B-17 design as a basis for the 307 Stratocruiser after Boeing had success in using the B-15 wing and engine system as a basis for the 314 Flying Boat. Here, as always, the goal was to increase the passenger-carrying capacity (seat miles per unit of time) at some reduction in cost per passenger mile by increasing size or speed of the aircraft, keeping in mind that increases in passenger comfort must proceed at the same time.

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<sup>1</sup>Ingles, Douglas J., The Plane that Changed the World, Aero Publishers, Inc., Fallbrook, CA, 1966, pp. 9-13.

<sup>2</sup>The cause of the crash was attributed to wing failure caused by dry rot in the wooden spar members. Regulations were passed which required periodic inspection of the wing members, thereby ostensibly making obsolete the plywood covered wooden wings of the Fokker. This milestone regulation was the forerunner of federal regulatory involvement which would effect significant increases in safety over the years to come.

Thus, we see that progress in Technology has made possible

increases in passenger size per unit

increase in speed per unit (reduction in time of flight)

(for instance, see Fig. 2)

decreases in cost per unit to operate

increases in comfort

increases in safety

increases in traffic volume

reduction in fares to user with fare set to

compete with other modes of travel

increases in profit to operator and owner investor<sup>1</sup>

Technological breakthroughs, like the all-metal cantilever wing, constant speed propeller, exhaust gas superchargers, pressurized cabins, the jet engine, the swept wing, the supercritical airfoil, occur rarely. The continued increases in productivity<sup>2</sup> have come about by the clever integration of a number of modest advances in aerodynamics, engines, materials and structures into the design of a new aircraft. The purchase of a new aircraft occurs when the market demands increase to the extent that the airlines need new aircraft and are in a strong enough financial position to commit to a major equipment investment. Further, the financial community must judge the airlines to be a good risk given predictable regulatory environment. And, finally, the manufacturer must see a large enough market to be reasonably certain of a fair and timely profit on the R&D and production costs. The manufacturer will then incorporate as many of the accumulated technology advancements into the new design as will result in the performance advance which will meet the airlines requirements with acceptable risk to the manufacturer.

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<sup>1</sup>However, it is the intention of the CAB in setting fares and licensing routes to keep profits at or below a certain percentage that will provide a reasonable return to the operators, as well as reasonable fares to the user.

<sup>2</sup>See Appendix A for definition of productivity.

Individual modest advances in technologies also have been incorporated into major modifications of a given basic aircraft design. This "family" design concept is utilized by most manufacturers to increase its market for a given basic airplane design. Use of more advanced technology occurs to a lesser degree in such instances, however, because of the high cost of major redesign and production tooling changes.

While this discussion has focused on the aircraft, additional air transport system productivity increases have accrued to a large degree also by improvements in the air traffic control system, the ground passenger and aircraft services, and maintenance procedures. However, in the discussion that follows, we will concentrate on the aircraft component of this transport system.

#### ALPHA-BETA RELATIONSHIP

Enos has developed, in his analysis of the technology of petroleum refining, a conceptual framework of the innovative process which is quite useful for the air transport industry as well.<sup>1</sup> Simply put, this characterization involves a categorical division of any particular innovation into its so-called alpha and beta stages. The alpha stage may be described as the period of inventive activity on a particular innovation which precedes its introduction as a marketable commodity, whereas the beta phase refers to the process of technological change which occurs subsequent to this commercial introduction. (See Fig. 3 for graphic illustration.) Superficially, this may appear somewhat similar to the Schumpeterian distinction between innovation on the one hand and its subsequent imitation on the other, though as we shall clearly see in the instance of transport aircraft, the alpha and beta division does not correspond at all to the technologically active/passive division implied by Schumpeter's conceptual categories.

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<sup>1</sup> John Enos, *Petroleum, Progress and Profits*, M.I.T. Press, Cambridge 1962 (see an outline of this process in Table I).

Since we wish to study the air transport industry in terms of its alpha and beta phases, we must examine the development of the industry and its supporting equipment to identify when alpha phase changes occur. To do this we have listed the major technology advances incorporated into each new aircraft as it was introduced from 1928 to 1970. These data are presented in Table II. Examination of these data enables the grouping of the aircraft and separation into alpha and beta phases. This is presented in Table III, where you can see the major difference between alpha phases is the beginning of the capability to start a new generation. It should be noted that while we consider that the Boeing-247 did usher in a new generation (that of the twin-engine low-wing stressed skin monoplane thought of as the DC-3 generation) we do not consider that the DC-4 ushered in a new generation since it was not equipped with a pressurized cabin. The rest of the table follows in a natural sequence: four-engine pressurized machines, turbo jet swept wings, and large high by-pass ratio turbo fan vehicles (747, etc.).

It is useful to explore the implication of the alpha/beta conceptual framework somewhat further. First, instead of describing a particular innovation in isolation, these categories specify a relationship between a particular innovation and other innovations which either precede or follow that innovation temporarily. Thus, a particular innovation may either be examined as an alpha phase in relation to other innovations which follow it or as a beta phase relative to an innovation which preceded it. The concrete phenomena which we seek to conceptualize are the aspects of technological unevenness of development and of technological complementarity which are often present within innovative development but which appear to be of particular significance in the case of air transport. Thus, a particular innovation B may not yield any substantial increases in productivity unless it is preceded by innovation A, while the full productivity

gains of innovation A cannot be fully realized until the introduction of its complementary technology, B. An excellent example of this from the current state-of-the-art aircraft technology is the gas turbine engine (innovation A) and the swept back wing (innovation B). Until the jet engine introduced the possibility of efficiently extending the thrust of a power-plant through the speed of sound with viable efficiencies, there was no increased productivity to be gained from a swept-back wing. However, subsequent to the introduction of gas turbine propulsion, its full productivity potential<sup>1</sup> could not be achieved without the improvements offered by the complementary technology of wing sweep (which effectively raised the Mach number<sup>2</sup> to the maximum possible before transonic airflow and the attendant drag rise begins to occur on the wings). When the jet engine was introduced the limitations heretofore placed on aircraft speed (by the drop-off in effective thrust at higher speeds ( $M = 0.65 - 0.75$ )) was removed and a more effective way of increasing the cruising speed than reducing the wing thickness was required. This mechanism was the sweptback wing, which postponed the effects of compressible flow over the wing to a much higher forward speed. That these two technological advances appeared on the scene at about the same time is interesting but, in fact, fortuitous (when one jet engine was first conceived the use of sweepback to delay the drag rise had not been suggested).

The first installation of jet engines in military aircraft was in straight-wing craft. The Germans incorporated the sweep-back principle into their second generation jet aircraft while the Americans and British did not make the step until shortly after WWII (following their unearthing of the horde of German data on swept-wing configurations.) Yet, the first installation of a jet engine

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<sup>1</sup>It should be realized that the overall compression ratio of the jet engine system increases as the true operational air speed increases and it can be shown that the overall efficiency of operation for the true jet is greater than the reciprocating engine plus propeller in the vicinity of  $M=1$  even if the propeller efficiency does not fall due to the effects of Mach number on the propeller itself; therefore, it is important to operate the jet at as high a speed as possible.

<sup>2</sup>Mach number is the ratio of the aircraft speed to the speed of sound in the outside air.

in a transport-type aircraft was in the DeHaviland Comet which could not capitalize on its speed and altitude (comfort) advantage due to certain basic flaws in the fuselage structural design and construction (fatigue failure); by the time this problem was solved, the die was cast for the appearance of the U.S. swept-wing jet transports, which were not only larger and faster, but could span the U.S. or the North Atlantic nonstop with reductions in direct operating costs below those of current machines. Virtually all major technological advances within the air transport industry correspond to this model of the combined interaction of technological unevenness and technological complementarity as discussed elsewhere in this paper. The interplay generally is between a number of technological innovations, not just two, as in this example.

We can pursue the quantitative relationship between the alpha and beta phases of aircraft technology and their subsequent impact upon productivity at several levels of analysis. For example, we may identify particular innovations at the level of transport aircraft generations, where the relevant generations may be thought of as (1) the movement from single engine biplanes to 2-3 engine biplane and high-wing monoplanes; (2) from these multi-engine biplanes and high-wing monoplanes to all-metal stressed skin twin-engine low-wing monoplanes; then to (3) four reciprocating engine pressurized aircraft; to (4) turbo-propeller aircraft; to (5) turbo-jet, with swept wings, and finally (6) large high by-pass ratio turbo-fan aircraft.<sup>1</sup> These relevant generations and sources of their characteristics are noted on Table III. At a less macroscopic level, we can examine the technological innovation process within each of these generations, or, finally, at the level of particular aircraft models within each of these particular generations.

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<sup>1</sup>The somewhat arbitrary nature of this definition of generations is difficult to avoid. For example, one could convincingly argue that all-metal strut-wing monoplanes are substantially different than their cantilever winged successors, and that wide-bodied turbo-jets are likewise separable from the narrow fuselage predecessors, though neither of these distinctions is accomplished by our categorization. A critical consideration here is a sufficient aggregate data series to characterize the alpha and beta phases of the generations defined.



### Technological Change Between Generations

Although the qualitative aspects of each generation enumerated above are briefly described by such variables as construction material, engine number or engine type, it should be clear from our discussion of the critical importance of the phenomenon of complementarities within technologies that we are in fact differentiating organically integrated aircraft types which necessarily differ radically in many additional characteristics from generation to generation. These differences are measured by factors such as cruise speed, cruise altitude range, wing-loading, payload, the aerodynamic parameters of lift and drag, and so on. Clearly, all the complementary technologies must be developed to a higher level to realize a generational transition: one does not achieve a modern jet aircraft by just mounting turbojet pods on a DC-3 airframe.

We may even identify the innovation of air transportation itself as the particular technological advance. Compared with the railroad or bus industry, it is especially difficult to establish a quantitative measure which embraces the huge quantitative technological shift represented by aircraft relative to preceding and substitute modes of transportation, thus making it difficult to ascertain the productivity advances attributable to innovative activity of the alpha phase.<sup>1</sup> However, it is much more straightforward to document the operating cost improvements attributable to the beta phase of air transportation.<sup>2</sup>

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<sup>1</sup>The matter is, in reality, even more complicated. When did the "pre-history" of the airplane end? Although the Wright Brothers established the technical feasibility of powered flight on that momentous day in 1903 in Kitty Hawk, the innovation of the airplane as a commercial proposition was still far from achievement. It was a long way from Kitty Hawk to the point where a new form of passenger transportation may be said to have become available in the sense of functioning as a serious competitor to the existing forms of transportation. This occurred in 1919 in the U.S., England, France, and Germany by adaptation of military aircraft for this purpose (see pp. 183-184, Gibb-Smith, C. H., Aviation, an historical survey from its origin to end of WWI, London HM 90, 1970).

<sup>2</sup>This summary is further elaborated in the Appendix B.

For example, from 1929 to 1953, Kendrick<sup>1</sup> has established that output per unit of labor in air transportation increased by 660%. Over another period, 1928-1968, the cost per available seat mile (in constant (1954) dollars) dropped from 13.40 cents for the Fokker "Super Universal" aircraft to 0.93 cents for the DC-8 turbo-jet, or just 1/14 of the 1928 levels.<sup>2</sup> Even if we restrict our time series to the period corresponding to so-called modern transport aviation, dating from around 1936, these improvements are equally impressive. For example, the labor productivity for the entire period 1928-1953 increased by an average of over 8% per year, while the corresponding figure for the shorter 1936-1953 period is more than a 7% improvement per year on the average.

Another dramatic quantitative measure of the advances made in airline technology and productivity is demonstrated by a calculation of "social savings" which have been realized in the industry.<sup>3</sup> At 1964 traffic levels, using the technology available in 1933 to provide an equivalent sized air transport system would have cost \$8.293 billion, whereas the actual expense was \$1.701 billion (all 1954 dollars), thus representing a social savings of \$6.592 billion, or over 80% of the amount using the 1933 technology.<sup>4</sup>

We can gain some further insight into the relative importance of the alpha and beta phase improvements if we focus upon the inter-generational data, where

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<sup>1</sup>Kendrick, John W. *Productivity Trends in the United States*, Princeton University Press, Princeton, N. J., 1961, p. 555.

<sup>2</sup>Phillips, Almarin, *Technology and Market Structure*, Heath Lexington Books, Lexington, Mass., 1971, pp. 40-51.

<sup>3</sup>On the concept of social savings and its detailed elaboration with respect to the railroad industry, see Robert Fogel, *Railroads and American Economic Growth*, Johns Hopkins Press, Baltimore, 1964.

<sup>4</sup>For this calculation see Figure A-II (Appendix B).

transitions between subsequent generations are regarded as alpha technological shifts and the intra-generational improvements are regarded as the beta technological shifts. The relevant data are summarized in Figures 4 and 5, which plot the cost per available passenger seat mile and the productivity index, "aircraft seat miles per hour," for the aircraft used in the U. S. air transport industry for their first year in commercial service, their introduction dates spanning the period from 1928-1970. Perhaps the most striking aspect of this focus, in terms of our alpha/beta model of innovation, is the apparent continuity across generations. Upon reflection, this is hardly surprising, since we may assume an unwillingness to adopt a new model (innovation) until its costs and usefulness reach the point where its adoption represents a substantial improvement. When the innovation reaches this point, the potential benefits and the projected growth are likely to become substantial. As noted previously, an aircraft company will not undertake the costly design/development of a new model aircraft until it is reasonably assured of a large market; i.e., large enough to retire development and start up costs in a reasonable period of time. The airlines generally will buy a new model aircraft when they have a need--either new routes requiring new capabilities, new capabilities required to meet competition, new capabilities to meet revised regulatory requirements, new capabilities to keep operating costs down, or the approach to the end of the life cycle for their existing aircraft fleet.<sup>1</sup> Financial status of the airlines also wields a strong influence in that the introduction of new aircraft should ensure a reasonable increase in return on investment over continued acquisition and use of existing aircraft currently in production.

Before we discuss the progression with time of the air transport industry growth characteristics that relate to the alpha or beta phase development, we

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<sup>1</sup>This is very difficult to assess. In the 1926-29 time period the aircraft were written off in 3 years and replaced. Now, in the 1960-70 time period, the life can be 17 years or more.

should examine in some detail how the first low-wing all-metal twin engine transports came into being since they set the stage for the rapid expansion of the air transport industry in the 1930's. We shall review the genesis of the Boeing 247 and its follow-on and nemesis the DC-1, 2, and 3 series aircraft.

BOEING-247 GENESIS - Bill Boeing, who had a reasonable business in building military airplanes, wanted to get into the commercial aircraft field. Of his first mail plane, the Model 40, he only sold one to the Post Office Department.

However, because of the Air Mail Act of 1925, the Post Office was to turn over the job of flying the mail to qualified private operators. Boeing redesigned the Boeing Model-40 to use a Pratt-Whitney Wasp engine for use as a combination mail and passenger plane and, together with Edward Hubbard, bid on the contract air mail route (CAM-18) from Chicago to San Francisco.<sup>1</sup> They won the bid, posted a performance bond and formed a separate company "Boeing Air Transport," to do the flying. The aircraft to be used were Boeing Model-40A's, which could carry 1000 lbs of mail plus two passengers (at \$200 each per one-way trip).

Boeing built 25 aircraft and stationed them along the route to start service by July 1, 1927. This route was 2000 miles long and took 23 hours to traverse.

The Model 40A's were replaced by 40B4's with 4-passenger capacity,<sup>2</sup> and the overall passenger traffic climbed to such an extent that bigger machines were needed, especially since competition in the form of Transcontinental Air Transport equipped with Ford trimotors was to begin on July 9, 1929 as an air/rail service from New York to Los Angeles.

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<sup>1</sup>Smith, Henry L., Airways, The History of Commercial Aviation in the United States, A. A. Knopf, New York, 1942, p.119.

<sup>2</sup>Ingles, Douglas J., 747; Story of the Boeing Super Jet. Aero Publishers, Inc., Fallbrook, CA, 1970.

Boeing introduced the Model 80, a trimotor biplane with 12-passenger capacity even before the July 9, 1929 start date. This was followed by the Model 80A with accommodations for 18 and a crew of 3. The use of NACA cowlings on the 80A increased the cruising speed by 10 mph.<sup>1</sup>

To further increase the income of United Air Lines (which was part of a combine composed of Boeing Air Transport in a merger with Boeing Aircraft, Pratt-Whitney, Hamilton Standard, and Chance Vought called United Aircraft Transport Corporation) an attempt was made to build a for-mail-only aircraft that was faster and more economical than the 80A. This could be done successfully, Boeing figured, because the airmail subsidy was figured on a weight-mile basis.

Experience with metal-covered pursuit airplanes for the military gave Boeing sufficient confidence to build a single-engine all-metal low-wing monoplane known as the Monomail (Model 200) which carried no passengers but could carry 1000 lbs of mail at 158 mph over the route. It was one of the fastest aircraft in the air at the time (first flew on May 6, 1930).

However, before this machine could be put to use, the McNary-Watres Act was passed (April 29, 1930) and changed the airmail rate structure from emphasizing dollars per pound per mile to dollars per unit volume cargo space per mile, plus extra for passenger-carrying capacity, over-the-mountains flying, night operations and other variables. Subsequent modifications to the Monomail did not yield a satisfactory passenger-carrying option and Boeing was forced to look elsewhere while still operating the 80A's. During this period, TWA was formed and began to operate Ford Trimotors and Fokker F-32's which were bigger and faster than the 80A's.

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<sup>1</sup>Bowers, Peter M., Boeing Aircraft Since 1916, Putnam, London, 2nd Ed., 1968.

Boeing had just participated in a high-speed bomber competition and while they lost to Martin they produced, in the spring of 1931, a unique twin-engine all-metal machine that was very fast and, along with the Martin machine, set the stage for bombers for the next decade. Boeing continued to amass experience with all-metal aircraft in the P-26 Pursuit aircraft design.

With the pressure of competition becoming greater from TWA, United Air Lines requested that Boeing build them a new machine based on the twin-engine bomber design. The aircraft that resulted from this effort was the Boeing 247, a 10-passenger machine that could cruise 50-70 mph faster than any other airliner and was more economical. In addition, the direct operating cost (D.O.C.) was reduced from 10.81¢/ASM<sup>1</sup> for the Boeing 80A to 7.78¢/ASM for the 247, at the same time the cruising speed went up from 125 mph to 180 mph, and the time required to travel from New York to San Francisco went down from 27 hours to 19-1/2 hours. She was equipped with deicing devices on the wing and tail leading edges, controllable pitch propeller, retractable landing gear, an automatic pilot, cabin soundproofing, and trim and boost tabs on the control surface, and could fly over any obstacle on the route with one engine out. United Aircraft and Transport Corp. ordered 60 of these aircraft; the first to be delivered in July 1933. This machine, Boeing felt, would put them into a position to dominate the market, a long-time goal of United Air Lines.

DC-1, 2, & 3 ORIGINS - In any history of the U.S. air transport industry, the cardinal point of the development of the DC-3 is referred to time and time again. It is desirable to understand how this came about and what the motivating forces were that led to its development.

Basically, it can be said that Douglas was responding directly to a letter of request from TWA (Jack Frye, letter dated 8/2/32) for an airplane to compete

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<sup>1</sup>Aircraft Seat Mile.

with the Boeing-247 soon to be introduced by United Air Lines on its run from Chicago to the West Coast.<sup>1</sup>

The drive away from plywood-covered machines was brought to a head by the Knute Rockne crash on March 31, 1931 in a Fokker F-10 trimotor in Kansas, and the attendant requirement by the Bureau of Air Commerce that immediate and periodic inspections on plywood-covered aircraft be carried out.<sup>2</sup> (The Fokkers were red-tagged until this inspection could be carried out.) This was not economically feasible on these aircraft, as it entailed complete removal and regluing of the wing plywood surfaces. Since the presently available Fokker machines were all equipped with plywood surfaces, they were essentially grounded. This forced TWA to stop flying Fokkers and use Ford trimotors exclusively. These were safe and economical but noisy and slow. In addition, United Air Lines who was in neck-and-neck competition with TWA in the east-west air transportation race had just contracted with Boeing to build 60 twin engine all-metal transports based on the experiences gained with the Boeing entry in the Army Air Force all-metal bomber competition of 1931. After TWA was rebuffed in buying these new transports from Boeing (at least until UAL was equipped with them), Jack Frye and staff laid out the requirements for a new transport to compete with the Boeing 247. These letters of request were sent in August 1932 to five manufacturers--Douglas included. Douglas responded and the result was the DC-2 put into service in May 1934. This machine was based on Douglas' long experience in producing military aircraft, as well as the experience of its recently acquired subsidiary Northrop Aircraft who had pioneered in the construction of low-wing all-metal monoplane aircraft. Since Douglas had the

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<sup>1</sup>Ingles, Douglas J., The Plane that Changed the World, Aero Publishers, Inc., Fallbrook, CA, 1966, p. 19.

<sup>2</sup>Ibid - pp. 9-13.

Boeing-247 layout to go by it could only improve on it, and did. The DC-1 and DC-2 met the challenge of the 247 and laid the groundwork for the DC-3 introduced in 1936 which became the standard for the airlines between 1936 and 1939.<sup>1</sup>

In the discussion that follows, we regard as a measure of productivity the product of aircraft seats times cruising speed ( $AS \times V_C$ ). Costs per available seat miles are examined at the same time to ensure a viable aircraft. These two factors must be examined together until such a time as the data are available to treat productivity in a more classical sense.<sup>2</sup> A cursory examination of the data shown on Figs. 4 & 5 indicates that since all-metal stressed skin transport aircraft appeared on the scene in 1933, in the U.S., the ability to carry passengers increased, as represented by the factor  $A_S \times V_C$  by 20-fold in 40 years while the costs per seat mile have decreased by a factor of 10. These data indicate a steady progression of improvement in aircraft productivity ( $A_S V_C$ ) and reduction at the

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<sup>1</sup>It should be noted here that the DST/DC-3 was built to order of American Airlines, and did not represent a proposal by the manufacturer to an airline.

<sup>2</sup>We would ideally like to measure the productivity of civil transport aircraft in physical units such as the number of passengers it is possible to deliver over a specified distance in a specified time per unit of labor and capital. However, not only are these data unavailable to us in general, for the purposes of our analysis it is further necessary to disaggregate productivity across particular aircraft. Moreover, since the relative capital intensity of the air transport industry has not remained constant over the historical period of interest to us, there is no straightforward way to define a unit of "labor and capital." The measures generally available to stand as surrogates for productivity are direct operating costs per available passenger seat mile on the one hand, and available seats times aircraft velocity on the other. Clearly, each of these has its advantages and disadvantages, and each abstracts from important aspects of the productivity of the aircraft, though it is an empirical reality that the trend of one measure is closely correlated with the inverse of the other. In any case, we have chosen to present both of these criteria which taken together give the reader a feeling of the overall picture of productivity increase. We wish to include the costs directly, since we believe this to be a central decision variable in the process of aircraft innovation. Though not totally adequate in its inclusion of productivity, these costs would seem to be a necessary condition for the alternative measure of productivity to be of any relevance whatever.



same time in D.O.C. as each new aircraft was introduced. Of special interest is the jump in productivity following WWII for the Martin-202 and Convair-440 series aircraft. This jump was almost equivalent to that brought about by the introduction of the 4-engine transports, the Boeing-307 and the DC-4. However, these aircraft classes were designed with a different set of operating conditions, the 4-engine machines being larger range, ultimately being able to fly coast-to-coast before giving way to the jets. Also shown on these charts is the Comet, a 4-engine jet transport with a slightly swept wing introduced in 1952; note the high value of DOC upon introduction which was acceptable at the time because of the uniqueness of the travel offered; i.e., speed and comfort. The Comet operation was very successful until two machines were lost by fuselage fatigue failures and all airline useage ceased until 2-3 months before the Boeing-707 was introduced into service. However, by the time the 707 was introduced, the DOC of the Comet had been reduced only to that of the DC-7C, the productivity of the Comet was still 30% less than that of the 707, and due to the hiatus of the operation never really recovered its place in the marketplace.

Examination of Figs. 4 & 5 for comparisons of increases in productivity and reductions in cost in the alpha and beta phases indicates that these criteria show positive jumps at the outset of a new generation; i.e., at the beginning of the alpha phase. However, the subsequent improvements are not the same for the various generations. Whereas the costs continue to decline as each new model is introduced and the productivity does usually increase this trend does not always continue. The costs tend to go down during the beta phase but the productivity does not always increase. This suggests that other factors are at work, such as matching the vehicle more closely to the market demand, to provide jet service to more people (examine points for 707, DC-8, 720, 990, and 727). Table IV has been prepared to indicate roughly the gains in

productivity and reduction in direct operating costs (DOC) for the alpha phase from 1940 to 1970. At the introduction of each new series, there is a gain in both productivity and cost reduction, as well as speed increases, except for the Comet. However, in considering the Comet as a start of the alpha phases, it should be regarded as a false start since it only gave speed increase at a tremendous sacrifice in both productivity and DOC with respect to the presently available reciprocating engined Lockheed 1049C; however, when the 707/DC8 series were introduced, they provided increases in speed, productivity and reductions in DOC over the available 4-engine prop driven aircraft (1049C and DC7C) to make their introduction viable. The wide body, high bypass ratio jet fan series has been included to show that while the speed advantage was small, the large increase in size and use of a more efficient engine gives a tremendous increase in both productivity and reduction in DOC.

#### Technological Change Within Generations

In the beta phase, growth is accomplished by three factors (see Table I):

- o construction of larger units
- o adoption of ancillary advances by other industries
- o increase in operating skill or know-how

In the main, the productivity gains and cost reductions achieved in the beta phase have been due to the construction of larger units and have been impressive and usually larger than that realized in the generational shift - alpha phase. From 1933 to 1956, for example, costs per passenger seat mile for two-engine aircraft declined from 7.75¢ to 2.20¢, or down to less than 1/3 of the original level of the Boeing 247, while productivity rose from an AS x  $V_c$  of 1800 to 14,600. Similarly, for the beta phase of the four-engine generation, costs dropped from 3.22¢ in 1940 to 1.80¢ in 1953, almost halving it in 13 years,

while the productivity rose from 9400 to 25,000 and the cruising speed rose from 200 to 300 mph. In the five years of the data available for the turbojet, direct operating costs declined from around 1.7¢ to 1.15¢ for the newly introduced vehicles while the productivity actually went down (basically because of no essential growth in speed and size as the smaller model sizes adapted to new market segments. However, later in a discussion of the DC-8 development a growth of productivity along with reduction in costs is noted).

Examination of the data shown in Figs. 4 & 5 in terms of lumped gains for the beta phase (Table V) shows that the DC-3 generation progress resulted in gains in productivity of 710% or 12,800, and cost reduction in DOC of 5.6¢ as compared with the alpha shift gains for the DC-3 series to the 307 series of 150% or 5700, and 1.55¢ respectively. This trend is also apparent for the 307 generation only if you consider the jet series starts with the Comet; i.e., 169% or 15,800 and 1.32¢, compared with 129% or 12,100 and -1.03¢ for the beta and alpha phase comparisons. Although there is no specific comparative data available from Miller and Sawers for the Turbojets past 1965, these aircraft have grown during the beta phase in such a way as to increase aircraft productivity and reduce direct operating costs.

Also shown in Figs. 4 & 5 are some estimated data for the wide-body series of high by-pass ratio turbofan aircraft. It is seen that these machines, at their introduction, have produced large gains in productivity with attendant reductions in the direct operating costs; mainly because of their increase in passenger-carrying capacity and use of high by-pass ratio jet fans with much lower fuel consumption. At the present time, all of these machines are undergoing beta phase changes to adjust the passenger-carrying capacity to the market by either reducing or lengthening the fuselage.

Examples of increases in operating skill and know-how affecting operating costs right down to particular aircraft, within each of the above generations as well, are summarized in Figs. 6, 7, and 8.

Looking first at piston vehicles, we see from Fig. 6 that this phase of the 2-engine Boeing-247 operating history experienced a decline in D.O.C. from nearly 7¢ per available seat mile at its inception down to slightly over 5¢ 7 years later (in constant 1954 dollars). This represents a respectable 6.1% per year reduction in costs. The relative cost reduction for particular 4-engine piston vehicles appears to be somewhat larger, a 7.7% per year cost reduction per available passenger mile. For this machine, there was no basic change in productivity over this period.

Within the turbo-prop generation, we see that the Lockheed L-188 Electra costs dropped an average of 7% per year, as seen in Fig. 7. This trend continues through the current generation of turbojets as well and, if anything, the relative cost reduction achieved for a particular aircraft through its life span seems to be increasing for the more recent generations. From Fig. 8, we may calculate that, for the Boeing-707 over its first 5 years of operation, direct operating costs per seat mile dropped an average of 8.7% per year, from 1.56¢ in 1959 to 1.0¢ in 1964.

The discussion thus far has considered the single dimension of costs per passenger seat mile or that in conjunction with a productivity factor ( $AS \times V_c$ ). However, over the historical development of the air transport industry, these figures necessarily understate and provide a lower bound estimate for the extraordinary qualitative transition which the industry has experienced over this same span of time. Dimensions such as range of aircraft, aircraft ride quality, all weather operations, noise and other amenity factors, and safety improvements, are at best very inadequately reflected in the numerical data on direct operating

costs (even since speed is not fully reflected in conventional productivity measures, since such measures do not really incorporate greater passenger comfort and convenience).

If, for example, a DC-3 had the same cost/passenger mile as a 707, we would never be led to conclude that they are congruent vehicles. Some of these improvements can be quantitatively documented along other dimensions than cost. For example, aerodynamic efficiency, as measured by product of Mach number and lift divided by drag, which aggregates the results of several particular technological developments such as increasing engine thrust, improved airfoil design, and so on, has increased over five-fold from the DC-3 to the 707.<sup>1</sup>

The trend of aerodynamic efficiency for several particular aircraft is documented in Fig. 9. Similarly, we can observe in Fig. 10 the substantial progress in noise abatement for turbine aircraft since their inception in 1958 to the present, where a reduction in the deciBel levels of take-off noise have dropped from over 120 to about 93 in 1974 with the 747 aircraft.<sup>2</sup> These qualitative improvements that do not decrease drag or fuel consumption but increase weight such as noise reduction modifications to both the engine system and the aircraft undoubtedly add to the costs of operation and so would tend to counteract the secularly declining costs per available passenger seat mile.

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<sup>1</sup>Boeing Commercial Airplane Company, Document B-7210-2-418, Oct. 5, 1976, p. 3, and Fig. 6.

<sup>2</sup>Ibid., p. 3 and Fig. 7.

### Characteristics of Beta Innovation

There are basically two types of activities within the beta phase of the innovative process which lead to the productivity gains we have witnessed above.

One such activity may be categorized as "learning-by-doing." There is now a considerable body of literature describing the improvements in productivity which have been associated with learning to manufacture a newly conceived product. Indeed, in some circles the phenomenon is referred to as the "Horndal Effect," after the Swedish steelworks where, over a period of 15 years, output per man hour was observed to increase about 2% per year even though no changes had occurred in either the plant or production techniques. The phenomenon has been further documented, not only in air-frame production, but in machine tools, shipbuilding and textiles as well.<sup>1,2</sup>

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<sup>1</sup>A. Alchian, "Reliability of Progress Curves in Airframe Production," Econometrica, October 1963, pp. 679-92; Werner Hirsch, "Firm Progress Ratios," Econometrica, April 1956, pp. 136-43; Leonard Rapping, "Learning and World War II Production Functions," Review of Economics and Statistics, 1965, pp. 81-86; Paul David, "Learning by Doing and Tariff Protection: A Reconsideration of the Case of the Ante-Bellum U.S. Cotton Textile Industry," Journal of Economic History, Sept. 1970, pp. 521-601; Kenneth Arrow, "The Economic Implications of Learning by Doing," Review of Economic Studies, June 1962, pp. 155-73. According to Hirsch, the U.S. Air Force "for quite some time had recognized that the direct labor input per airframe declined substantially as cumulative airframe output went up. The Stanford Research Institute and the RAND Corporation initiated extensive studies in the late forties, and the early conclusions were that, insofar as World War II airframe data were concerned, doubling cumulative airframe output was accompanied by an average reduction in direct labor requirements of about 20%. This meant that the average labor requirement after doubling quantities of output was about 80% of what it had been before. Soon the aircraft industry began talking about the 'eighty percent curve'." Hirsch, op. cit., p. 136. It is possible, of course, that cost reductions which have been attributed to learning by doing have actually been due to other factors which have not been correctly identified, especially in cases where learning by doing has been defined as a residual. For earlier discussions of the learning curve in the aircraft industry, see Adolph Rohrbach, "Economical Production of All-Metal Airplanes and Seaplanes," Journal of the Society of Automotive Engineers, January 1927, pp. 57-66, and T. P. Wright, "Factors Affecting the Cost of Airplanes," Journal of the Aeronautical Sciences, February 1936, pp. 122-128.

<sup>2</sup>Subsequent to the preparation of this paper, a reference to the learning curve phenomena as applied to aircraft construction was discovered in a book by Berghell entitled "Production Engineering in the Aircraft Industry" (see Chap XII pp. 166-198) that was written for the Engineering, Science, and Management War Training Program and published in 1944 by McGraw-Hill.

We wish to emphasize here, however, a different but related form of learning-by-doing. Not only does learning-by-doing take place in the manufacturing process as workers improve their skill in the making of the product, but, as a result of the actual use of the aircraft itself, a considerable learning process occurs which reduces the operating costs of the aircraft in use after its manufacture. Much of the learn-by-doing in aircraft has been associated with the gradually growing body of experience associated with the operation of a new model airplane.<sup>1</sup> The experience is, perhaps, most characteristic of complex final products with elaborately differentiated but interdependent component parts, and is therefore related to the complementarity phenomenon. Operating cost reductions, as we will see, depend heavily upon gradually learning more, during the actual operation of a new aircraft, about the performance characteristics of an airplane system and its components, and therefore understanding more clearly its eventual full potential. For example, it is only through extensive usage that detailed knowledge is developed about engine operation, their maintenance needs, their minimum servicing and overhaul requirements, etc. This is due partly to an inevitable--and highly desirable--overcautiousness on the part of the manufacturer in dealing with an untried product. As experience accumulates, it becomes possible to extend the operating life beyond original expectations.

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<sup>1</sup>A parallel process, with which we do not deal, is the extensive learning which was involved in the operation and management of an entire aircraft fleet. There were many operational problems for which optimal procedures had to be developed--scheduling problems, turnaround time, dovetailing the requirements of equipment with those of personnel, etc. Such "software" responsibilities belong to the realm of management and not technology, although the two realms are obviously interrelated.

A point which deserves to be made explicit in all this is the persistent importance of uncertainty in the precision of prediction of performance in airplane design. In spite of elaborate possibilities for prior experimentation in wind tunnels of increasing sophistication and theoretical techniques of increasing precision in aerodynamic research, such things as scale effects and the phenomena of compressibility and turbulence continue to result in unexpected outcomes of a positive as well as negative nature. Sometimes performance exceeds expectations and sometimes there are unexpected benefits as well as unexpected problems. Wind tunnel tests in the past, for example, have resulted in exaggeration of the increase in drag, particularly at transonic speeds, and handling problems associated, for example, with a swept-back wing design. One must not exaggerate, therefore, the extent to which, even today, the design of aircraft can draw upon precise scientific methodology to achieve its ends.<sup>1</sup>

Secondly, we have the technological advances embodied in the hardware of the aircraft. One excellent means of gaining insight into how several complementary technological advances occur at uneven intervals is to describe the process as it occurs for a particular aircraft. We may consider the case history of the Douglas DC-8 as representative of this process of development. Several of the events in this history are summarized in Fig. 11.

In the DC-8 we have an aircraft which has experienced a more than 50% reduction in operational energy costs over its life span on a per-seat-mile basis, as well as an increase in productivity ( $AS \times V_C$ ) from 62,500 for the DC8-10 30 & 50, to 130,000 for the DC8-61-63 series, although the basic configuration has been largely unchanged and, as we can see, the modifications have been relatively unsophisticated compared to differences between aircraft types.

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<sup>1</sup>Miller, Ronald and David Sawers, The Technical Development of Modern Aircraft, Praeger Publishers, N.Y., 1968, pp. 246-250. See also our later discussion of wind tunnel technology.



Clearly, an important set of modifications has had to do with the engines, which have progressed both to increase available thrust and decrease specific fuel consumption, thus increasing the potential payload and directly reducing operating costs. At the same time, there have been modifications to the wing profile that reduce the drag of the aircraft. With the DC-8-30, a drooped flap was added, then a leading edge extension with the DC-8-50. Subsequent models increased the aspect ratio and repositioned the flap.<sup>1</sup> Engine pylon design also underwent some modification. These variations on the aircraft's geometry were motivated by the drag reduction and consequent increased fuel economy they were able to provide. But it is clear from the figure that a third very substantial contribution to increasing the aircraft productivity has been the ability to stretch the aircraft, increasing capacity from 123 seats up to 251 seats, thus demonstrating the large leverage to be reaped by increasing the internal passenger capacity, provided of course they can be operated sufficiently close to capacity. The interdependence of these technological improvements is perhaps obvious but requires explicit exposition. The possibilities for stretching and consequently adding payload volume and weight to the vehicle depend upon having more powerful engines to meet the take-off incorporated in the wings to maintain approach and landing speed as well.

The story of the DC-8 is quite representative of the transport aircraft industry design philosophy. Innovations which have been incorporated within a particular vehicle and which have made substantial improvements in their operating cost characteristics predominantly have a good deal to do with engine development in terms of available thrust and fuel consumption capabilities,

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<sup>1</sup> While the modifications alter the aerodynamic parameters of the wing, sometimes substantially, the wing itself does not generally experience internal structural alterations. This is because of the prohibitively high cost of wing redesign which makes it much more economical to modify the flaps, leading edge and wing tips. At the same time, the possibility of eventually utilizing even these add-on devices must be anticipated to some degree during the initial wing development stage.

with reduction in overall drag by modification in wing design, and with stretching of the vehicle to increase payload capability. Although the dramatic improvements in operating costs may initially appear to come directly from the stretching process, this process is unattainable without the complementary developments of power plant technology and sometimes wing technology, themselves highly interdependent technologies. Engine technology in particular during the turbine era has experienced dramatic technological growth in terms of thrust per pound of engine weight, which has increased by over 50% in 20 years, but even more so in terms of fuel consumption per hour per pound of thrust. For example, in 1950, about 0.9 pounds of fuel were required for each hour-pound of thrust. By the early 1960's, this requirement, with the development of the turbo fans, dropped to around 0.75 pounds of fuel per hour-pound of thrust. With the innovation of the high bypass turbo fans around 1968 and in use today, the fuel requirements dropped to 0.6 pounds of fuel per hour-pound of thrust. This 30% decline in fuel requirements over this period has direct implications for increasing the deliverable payload of aircraft within the turbine generation.<sup>1</sup>

The phenomenon of stretching as applied to jet transports from the Comet to the 747 is a classic example of a process which is not very "interesting" technologically but is of vital economic importance.<sup>2</sup> To begin with, the process reflects the basic complementarity between the performance of the engine and the airframe. Indeed, there is little incentive to improve engine

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<sup>1</sup> Boeing Commercial Airplane Co., op. cit. p. 4, and Fig. 4, reproduced herein as Fig. 21.

<sup>2</sup> The technique of stretching has a much older history and was applied with great success to the DC6-DC7C series as well as the Lockheed 649 to 1049H series of propeller driven aircraft. A well documented recent example of this technique is shown in the case of the DC9 series aircraft in Business Week (pp. 95 & 100, Nov. 14, 1977) where the DC9 series has been increased in size by lengthening the fuselage from 104.4 ft. (80 passengers) in 1965 to 147.8 ft. (155 passengers) in 1980 in five distinct steps. In addition, modifications to the wing and power plant have enabled it to increase performance and keep abreast of the latest noise regulations.

design unless airframe designers know how to exploit the improvement.<sup>1</sup> The carrying capacity of the airplane depends, first of all on the capacity of the engines. As engine performance is improved, exploitation of the potential requires redesign or modification of the airframe. The simplest response, as improved engines become available, is merely to stretch the fuselages and add more seats. Indeed, as this phenomenon came to be better understood, most airplanes were deliberately designed in order to facilitate subsequent stretching. Although airplane designers at any time design to conform to the capacity of the engines, it is generally understood that improved and increased performance engines will be coming along within the lifetime of the model, and it is important to be in a position to exploit them. Since designers expect these future engine improvements (as well as other complementary technological improvements), they consciously attempt to design flexibility into the airplane. This applies especially to the design of the fuselage in such a way as to facilitate later stretching. Such stretching has constituted an important

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<sup>1</sup>The role of highly specialized producers, and the question of what constitutes the optimum degree of specialization from the point of view of technological innovation, are highly important questions which are still not very well understood. Specialist producers tend to be very good at improving, refining and modifying their specialized product. They tend not to be very good at devising the new innovation which may constitute the eventual successor to their product. They tend, in other words, to work within an established regime, but they do not usually make the innovations which establish a new regime. Thus, the horse-and-buggy makers did not contribute significantly to the development of the automobile; the steam locomotive makers played no role in the introduction of the diesel, and indeed expressed a total disinterest, until it was finally entrepreneured by General Motors; and the makers of piston engines did not play a prominent role, in England, Germany or the United States in the development and introduction of the jet engine. The severely circumscribed technological horizons of specialized producers--to some extent an inevitable "occupational hazard"--may help to account for what one recent book on the aircraft industry describes as "...an apparent proclivity on the part of once successful manufacturers to remain too long with the basic technology of their original success." Almarin Phillips, *op. cit.*, p. 91. The point is that intimate familiarity with an existing technology creates a strong disposition to work within that technology, and to make further modifications leading to its improvement and not to its displacement. Scribes may be expected to invent forms of shorthand, but not typewriters. However, if improved ones show up they will be adopted.

part of the productivity improvement which has been characteristic of the beta phase. Stretching may, indeed, be thought of as the process by which, as a result of accumulated knowledge and improved engine capabilities, the payload possibilities of a new airplane design are expanded to their fullest limits. Clearly, this is an economic as well as a technological phenomenon. When an original design is modified through the stretching process it is usually dictated by the growth of passenger demand or new route opportunities.

A less current but no less poignant example of the process of technological advance is the closely interrelated set of innovations which culminated in the Boeing 247/DC-3 series of vehicles. These aircraft represent a qualitative advance over the previous types of aircraft. These changes were so organically interdependent with each other that it is impossible to identify the technological advance of the Boeing 247/DC-3 with any particular innovation. In fact, the interdependence of these advances is such that none of them individually would have resulted in the substantial technological advance realized by this pioneering airplane. Central innovations in this process were higher wing loading, twin-engine, all-metal cantilever wing and integral monocoque fuselage construction, retractable landing gear, engine cowlings, flaps, and adequate engine thrust coupled with variable pitch propellers, all used first by others. These interdependencies can be most easily associated through the categories of lift, drag, thrust, and velocity. One obvious means to increase payload is to increase weight lifted by the wing in up-and-away flight (increase wing loading) which, for a given vehicle, can be accomplished by flying faster (requiring increased engine power), increasing the lift as the velocity squared and by also increasing the lifting capability of the wing in the takeoff and landing condition to maintain the landing and takeoff speeds the same. This means an increase in usable  $C_{L_{max}}^1$ , as well as an increase in installed power. The increased power is required

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<sup>1</sup> $C_{L_{max}}$  is the maximum lifting capability expressed in coefficient form; i.e., lift/wing area x stream dynamic pressure.

to accelerate the aircraft to the desired take-off end velocity in the presence of the ground and climb over a 50-foot obstacle within a proscribed distance.

Thus, a balance can be struck between wing area,  $C_{L_{max}}$ , and installed power to perform the take-off maneuver; the power required to cruise at the desired altitude being less than the maximum available power but within the minimum fuel consumption range.

Because the power to cruise is directly proportional to the overall drag of the airplane in the cruise configuration, any drag due to bumps, wires, landing gear, etc., not associated with lift must be minimized. The drag due to lift must be reduced also. The premium for reduced drag under this condition becomes substantial and was realized in the case of the B-247 by the utilization of streamlined semi-monoque construction, higher wing loading, increase wing span, the use of a cowled engine, retractable landing gear, and, in the case of the DC-1/DC-2, landing flaps as well to increase  $C_{L_{max}}$  and hence cut down the landing speed.

Another central problem in the design of aircraft which the DC-2-3 series addressed with substantially greater success than any of its predecessors was the difficulty of designing an aircraft which must function efficiently in different flight regimes of conflicting requirements. Not only must an aircraft be efficient in its high-speed cruise configuration (low drag with flaps and gear up--engine throttled back) but obviously it must be able to operate effectively at low speed in landing and takeoff as well; this latter function being particularly sensitive to fuel consumption. Takeoff and landing on one hand, and cruising on the other, require different wing profile and engine operating conditions for optimum operation. For example, the high lift wing configuration required to takeoff results in an inordinately high drag in the cruise configuration. In addition, operation at altitudes above the expected

enroute terrain with one engine out required low overall drag as well as powerful low drag control surfaces. These factors were significantly resolved by the use of wing flaps, retractable landing gear, variable pitch propellers, and aerodynamically balanced control surfaces in the DC-3 generation of aircraft. So all these innovations came together to form the "modern airliner."<sup>1</sup>

One interesting footnote to this process is that after the successful integration of these interdependent innovations in the DC-3, new difficulties arose as a result which had neither been present nor foreseen. With the improved lift-to-drag ratio characteristics of the basic airframe and the increased wing loadings being used the aircraft became difficult to land, due to the increased speed on the glide path, requiring a much flatter descent glide path which gave pilots less flexibility on landing maneuvers (less time to make corrections). In response to this need came a new control capability brought about over a span of several years by use of powerful flaps, adjustable stabilizers, controllable drag producing devices such as flap lip spoilers, reversible pitch propellers, and more closely balanced and trimmable control surfaces. These, in turn fed back to increase the efficiency of the aircraft in particular portions of the flight, such as takeoff, as well, perpetuating the process of unevenness of technological complementarity. These advances also led to increased efficiency at high altitudes (flight at speeds close to that for maximum L/D), though until the innovation of pressurized cabins with the Boeing 307, these efficiencies were unavailable to normal civilian air transport operation.<sup>2</sup>

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<sup>1</sup>See Miller & Sawers, op cit, p. 47-52 and Phillips, op cit, p. 115-126.

<sup>2</sup>The pressurized cabin, by making it possible to fly higher, was thus a tremendous boon. The DC-4, unpressurized, flew at around 10,000 feet. Pressurization raised flying altitudes to about 22,000 feet. Jets, eventually, made it possible to go up to 35,000 or 40,000 feet and thus to fly above the weather. This, coupled with strong identification radar, represented an immense improvement in efficiency, reliability and comfort. As flying altitudes increased, improvements in meteorological knowledge made a further contribution to transport efficiency. Information concerning the precise location of jet streams, derived from photographic weather satellites, were increasingly valuable, especially on long-range flights.

## Power Plant Maintenance

Proper power plant operation requires an extensive maintenance effort and in the case of the radial (reciprocating) engines resulted in complete overhaul after a specific time interval. In the case of the jet engine which is subsequently discussed herein, this interval began based on the experience with reciprocating engines and was extended as experience was gained.

Powerplant maintenance provides an additional excellent case study for the process of beta innovation which combines significant measures of both learning by doing and complementary hardware innovation. Improvement in maintenance characteristics of the propulsion system has very substantial implications for reducing the operating cost of aircraft systems.<sup>1</sup> Overall maintenance comprises typically 30% of all direct operating aircraft costs of labor and materials. Even this tends to understate the overall impact, since the opportunity cost of lost revenues due to unscheduled maintenance requirements may be substantial as well. For example, at American Airlines, over a 37-month period between 1972 and 1975, maintenance problems accounted for an average of 21% of all delay costs, reaching an annual average of over \$8 million per annum in lost delay costs attributed to maintenance.<sup>2</sup> In terms of direct operating costs, maintenance costs for current jet vehicles are roughly equal between airframe and propulsion systems, though the activities are somewhat differentiated in that airframe maintenance is more labor-intensive than engine maintenance.

An additional reason that powerplant maintenance technologies are particularly instructive for our purposes is that while we can see from the above figures that

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<sup>1</sup>See NASA Document CR-134645, "Economic Effects of Propulsion System Technology on Existing and Future Transport Aircraft," 1974, particularly Section II.

<sup>2</sup>See NASA Document RFP 1-15-5595, NAS 1-14284, "The Impact of Technology on Operating Economics of Existing and Future Transport Aircraft," 1976, pp. M760816-19.

this activity is an important factor and a significant contribution to relative operational costs, it is at the same time virtually invisible in terms of actual flight technology. Maintenance technology develops in the shop away from the actual aircraft in their flight environments and often advances in terms of knowledge and hardware technology independent of the flight configuration itself, though of course, maintenance considerations substantially effect the design of flight configurations as well. The increasing trend towards design integration and modular construction of major flight components such as the propulsion system is largely in response to the increased efficiency this affords the maintenance activity.

Another substantial contribution to cost reduction in the maintenance activity is the apparent economies of scale. Airline companies find it economical to concentrate maintenance activity in order to capture the scale economies from such facilities. This scale economy apparently outweighs the increased expense of routing each vehicle in the fleet periodically to the maintenance base (for example, the facility that United Airlines maintains in San Francisco and that American Airlines maintains in Tulsa).

The phenomenon which we seek to understand quantitatively bears a strong general resemblance to the intra-generational cost reduction advances for aircraft as a whole as described above. A typical cost of engine maintenance schedule is presented in Fig. 12, together with the particular trajectory for the Pratt & Whitney JT3D turbojet engine.<sup>1</sup> The rise of maintenance costs during the first year of introduction reflects the impact of early design problems which were not anticipated prior to the rigors encountered during actual on-line operations.

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<sup>1</sup> See NASA Document CR-134645, op. cit., Section II, Fig. II-1.



In the particular case of the JT3D, the design difficulties remedied through maintenance involved inordinate wear of parts due to high operating temperatures relative to the thermal stability of the lubricants used. After this point, the costs reflect a strong downward trend during which the maintenance costs dropped to typically 30% of initial levels over a decade of operation. It is the determinants of this cost reduction, the beta phase relative to the alpha technology of a newly introduced engine, which we seek to understand.

Of course, the two phases cannot be strictly separated in their entirety. Just as some design problems such as the lubrication difficulties of the JT3D get solved under the guise of maintenance, so are maintenance aspects of the future engine carefully examined and prepared during the design phase of the engine. This activity includes preparation of instruction manuals, tools for repair, ordering and inventorying of spare parts, personnel training, and so on. All of this represents complementary, though simultaneous, technological advance with respect to the introduction of the new engine.

But there is also apparently in terms of cost effectiveness a broad menu of complementary technologies which cannot be anticipated during the design states of the propulsion system. It is these small but cumulative technological contributions which result in the cost profile of Figure 4 which we seek to understand. One of the more striking aspects of this technological development is that, to a surprisingly large extent, it is not readily identified with particular new and innovative hardware configurations. Rather, the maintenance history of particular engines, especially the turbojet generation, reflects a very strong "learning by using" dimension, where prior knowledge based upon reciprocating propeller engines was largely inadequate to anticipate the durability and reliability of the gas turbine engines (indeed, that earlier

experience turned out to be positively misleading). This was further exacerbated by the fact that jet maintenance occurred first in the military, where cost considerations were not of overriding significance, and these procedures were necessarily modified to conform to the more explicitly commercial constraints of the civilian sector.

This phenomenon is clearly reflected in the history of the maintenance philosophies of the airlines, in conjunction with recommendations of engine manufacturers and requirements of the Federal Aviation Authority (FAA). It has often been the resolution of the conflicting concerns of these groups which has led to substantial adjustments of the maintenance activity. Basically, engine manufacturers are commissioned to design equipment which on the one hand can be operated profitably by the airlines and on the other hand meets or surpasses the safety requirements imposed by the FAA.

It is the latter, based upon the experience of reciprocating engines which, with the advent of gas turbines, led to systematic underestimation of reliability. For example, the early maintenance programs were based upon specifications of allowable time between overhauls (TBO's) measured in hours of operating time. These were strictly enforced and only extendable in increments of 200 hours and this only after relatively extensive testing over a sample of several devices. While this was perhaps justified initially due to the safety consideration and the ignorance of the capabilities of the new technology, these programs were excessively expensive since unnecessary maintenance work was being undertaken at excessively short intervals between overhaul.

When this was realized, the next stage was a modified TBO program which removed the obligatory disassembly conditional upon various tests and inspections. This situation has further evolved to the current situation where there are no mandatory schedules for reconditioning, this taking place as indicated by

routine tests which can be performed while the aircraft remains "in-line." Such examinations include the use of borescopes to check wear, analysis of used lubricants, and visual examination. At a less critical level, this trend was also in evidence. For example, in the case of the Boeing 707, inspections which were initially required on a daily basis have been stretched out to routine weekly surveillance.<sup>1</sup>

The increased aircraft availability resulting from this improved maintenance scheduling is clearly much more a matter of familiarity with the hardware than technological advances newly embodied in the hardware. However, there have been clear implications for the engine hardware resulting from the learning-by-using process we have described. Regarding the engine itself, providing maintenance on a need-only basis quickly pinpoints the factors which limit durability. This has resulted in redesign effort focussed upon these elements. Further, since it is no longer necessary to recondition an engine as a complete unit, the cost reduction advantages available from interchangeable modularity have been more readily exploitable. In addition, there has resulted significant technological advances in the diagnostic hardware used to ascertain the advisability of maintenance. For example, more sophisticated borescopes using television transmitters for monitoring, internal accelerometers to monitor vibrations, and the use of isotope pellets to detect metal fatigue and stress have all been introduced in the diagnostic phase of maintenance.

This change from a very conservative preventive maintenance program to one based upon diagnostic parameters is reflected in the statistics regarding the frequency of engine removals with respect to operating times, as shown in Fig. 13. Even within the new diagnostic maintenance regime, there is for several years a declining trend of engine removals for maintenance and repair.

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<sup>1</sup>Boeing Commercial Aircraft Company, op. cit., p. 3.

This is shown in Fig. 14, where a decline is noted for each of the first 10 years. After this, the engines reach the durability limits of major structural members, thus requiring increasingly frequent removal in the later years. Again, this understates the full impact of this new maintenance schedule program, since it does not include the substantial opportunity costs no longer foregone when aircraft must be pulled out of service for frequent but unnecessary maintenance. The significantly decreased down times permitted by the new programs keep the vehicles in revenue-producing service for a higher proportion of the aircraft's lifetime. The result of course is a significant increase in the output/capital ratio for the aircraft.

Finally, it is notable that the learning by using and associated complementary technologies dominate, with respect to costs, the trend towards higher costs of each repair for aircraft over their lifetime, which has risen as indicated by Fig. 15. There are several forces at work here, some of which tend to lower costs/per repair and others which raise these expenses, though the latter clearly dominate. The major determinant here actually again includes more design than maintenance, though since it occurs after the device is on line, the activity takes place formally within maintenance. If there are maintenance problems with major structural elements, and these certainly increase in frequency as the engine ages, then there is substantial motivation to redesign these members for increased reliability and durability, rather than simple replacement out of stocks.

Propulsion system maintenance thus provides a less than obvious and certainly nontrivial case study of how accumulating complementary technological advances are responsible for significant cost decrease and increased item availability, helping to fully realize the potential introduced by a radically new major innovation such as turbojet engines. This source of drastically

improved economic efficiency is not a new one; rather, it has long characterized the process by which the air transport industry has accommodated itself to the availability of new and untried equipment. Indeed, one authority on the industry has estimated that, between 1920 and 1936, engine maintenance costs of radial reciprocating engines fell by fully 80% and constituted the largest contribution which the engine manufacturer made to the development of air transport at that time.<sup>1</sup> The contribution, however, as we have emphasized, was not and could not have been made by the engine manufacturer alone, but was possible only in conjunction with the learning by using of the air transport carriers. This effect has been carried on into the jet transport application as well.

#### Characteristics of Alpha Innovation

Undoubtedly a significant reason that such a large portion of operating cost decreases are experienced during the beta rather than the alpha phase reflects some of the striking and unique aspects of the alpha phase of airline technology itself. The whole development process for aircraft has certainly gone through a major transition from the early days when "build it and test it" was the dominant and perhaps only feasible developmental strategy. This sufficed in large part right up through the DC-3 series which flew first as a single DC-1 prototype and subsequently as the limited edition DC-2. However, to follow this linear strategy of development today would be much more difficult, given the complexity and scale of modern vehicles, in addition to the economic infeasibility and the high risk of obsolescence which would impact the prototype if not those on the drawing board.

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<sup>1</sup> Miller and Sawers, op. cit., p. 89.

The increased complexity of individual aircraft is clearly reflected in the time intervening between a vehicle's conception and its delivery to the air transport industry.<sup>1</sup> We can readily see this trend for the several generations in Fig. 16. What began with as little as six months' development time in 1917 has expanded several-fold to where the time required to develop a modern jetliner from conception to tested flight and delivery can take up to seven or eight years. This trend not only reflects particular aircraft, but classes of aircraft as well with the more complex technologies of more recent generation requiring an expanded alpha phase as well.

The earlier point of obsolescence on the drawing board is also strongly corroborated by Fig. 16. With development periods extending to eight years while new aircraft are coming on line much more frequently clearly underscores this point.

There are two particular processes pertaining to the alpha phase of aircraft development which are helpful in characterizing this process. First is the activity of pre-flight aerodynamic testing, and second is the transfer of technology from military to civil aircraft.

The central element in pre-flight testing has been the wind tunnel, and a sketch of its historical development and use captures many significant aspects of the alpha phase technological process. From the days of the Wright Brothers the wind tunnel has been used as part of the design process, to study the aerodynamic characteristics of a scale model of the proposed airplane as well as to study effects of air flow on component parts such as airfoils, struts, wires, fuselages and propellers. From this information the form and the performance of

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<sup>1</sup>A vehicle is conceived in terms of extant technology. If we include the time required for the development of the technology, then the total delays are typically double those between conception and first service.

the aircraft was predicted. The designer has relied on the results of wind tunnel tests to check his calculations and to provide insight into what might be done to improve the performance of the specific design under consideration. When these calculations did not agree with what was expected; i.e., predicted high speed, stalling speed, or take-off distance, concern was raised as to what part of the design process was amiss.

During WWI the Germans, the French, and the English used wind tunnels<sup>1,2,3</sup> to research and develop airfoil profiles and aircraft configurations, the British using a closed-throat open-circuit type (NPL), the French an open-throat open-circuit type (EIFFEL), and the Germans under Prandtl developed a return-circuit open-throat wind tunnel. Because of the differences in size between the models used in the wind tunnel and the difficulties in making precise measurements of aircraft performance in flight, emphasis was placed on obtaining wind tunnels that would more accurately represent the conditions of full scale flight. Subsequently, wind tunnels of larger size and greater speed were developed in the late 20's and early 30's to cope with the problem of more effectively representing true conditions of flight. Because most of the problems associated with aircraft development occurred in the lower end of the speed regime such as take-off and landing, special emphasis was made to construct testing devices that would cover the speed range of full sized airplanes at true flight speeds. This can be done in two ways, one by building a wind tunnel in which a full size aircraft can be placed in wind velocity equal to that expected, or by building a scale model of the aircraft under study, placing it in a wind tunnel of smaller size and using

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<sup>1</sup>Millikan, C. B., Aerodynamics of the Airplane, John Wiley & Sons, Inc., N.Y., N.Y., 1941, p. 10-17.

<sup>2</sup>Pankhurst, R. C., Holden, D. W., Wind-Tunnel Technique, Sir Isaac Pitman & Sons, Ltd., 1952.

<sup>3</sup>Pope, Alan, Wind Tunnel Testing, John Wiley & Sons, N.Y., N.Y., 1947.

the laws of similitude determined by dimensional analysis calculate the expected forces to be encountered with a full size airplane. By such analysis the forces on the aircraft may be written

$$F = C_F \frac{1}{2} \rho V^2 S \text{ where } C_F = C_F(R, M)$$

and  $\rho$  = density

$V$  = velocity

$S$  = Reference area

$R$  = Reynolds No. =

$$\frac{\text{Inertia Force}}{\text{Viscous Force}} = \frac{\rho}{\mu} V \ell$$

$$M = \text{Mach No.} = \frac{\text{Inertia Force}}{\text{Elastic Force}} = V/a$$

and the Coefficient  $C_F$  is a pure number based on the Reynolds Number and Mach Number of the fluid.

For low Mach numbers the coefficient  $C_F$  does not change with  $R$  and the forces are a function of size ( $S$ ) and dynamic pressure  $\frac{\rho V^2}{2}$ .

Because it is less costly to test with smaller scale models, the first wind tunnels were much smaller than the full size aircraft. For a period of time in the 1920's, it was felt sufficient to extrapolate the effects of small size (scale) tests to true flight speeds (full scale) by use of tests conducted in a special device known as a variable density wind tunnel where the pressure in the stream is increased by a factor up to 20. Much work was done with such a device to define and develop optimum airfoil sections in the 1920's and 30's. This method, however, developed a high turbulence in the airstream and confused the results, so the modern pressure tunnels are specially constructed to minimize this turbulence by placement of screens in the settling chambers before the working section to break up the eddys in the stream. In addition, the model size was very small



and it has been found more convenient to work with a model of about 7-10-ft. span or go to full size. The first large wind tunnel used in the U.S. was the Propeller Research Tunnel at Langley Field, Virginia, where the NACA cowl was developed during its period of checkout, before the propeller dynamometer was available. Subsequently, the work leading to the optimum placing of nacelles on wings was started here. Because of the success of this work, the full scale wind tunnel with a working section (throat size) of 30x60 ft. was constructed at Langley to study aerodynamic characteristics of full sized aircraft. It proved such a success that a larger full-scale wind tunnel was constructed at Ames (size 40x80 ft.) during WWII. It can test full size aircraft up to a span of 72 feet at speeds up to 235 mph.

Because the speed and size of aircraft increased rapidly, the influence of Mach number began to dominate the performance characteristics of aircraft and hence the testing scene.<sup>1,2</sup> These effects occurred first in propeller design, with the advent of jet driven machines the possibility of exceeding the speed of sound existed and emphasis was placed on both high subsonic and low supersonic testing arrangements.

As an example of uneven technology itself, the ability to build large scale and high speed aircraft has always outstripped the ability of designers to provide complete pre-flight tests of these vehicles. This reached such proportions in the late 1940's and early 50's that before the development of the slotted throat transonic wind tunnel, tests for aircraft in the transonic region were conducted by the wing flow techniques; i.e., strapping models onto available high speed aircraft which then flew at high speeds to sense aerodynamic

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<sup>1</sup>Pope, Alan, and Harper, John J., Low Speed Wind Tunnel Testing, John Wiley & Sons, Inc., 1969.

<sup>2</sup>Pope, Alan, and Goin, Kenneth L., High Speed Wind Tunnel Testing, John Wiley & Sons, Inc., 1965.

performance.<sup>1</sup> The whole series of experimental "X-type" aircraft during this period derived from the inability to simulate adequately the transonic environment in which new aircraft must traverse if they were to fly at supersonic speeds.

As a consequence of this unevenness between aircraft design goals and test capability, the design procedure, particularly in the case of transonic aircraft, can be an intuitive and uncertain task, and one which is often unverified prior to flying of prototype units. The design process is somewhat conservative to avoid the penalties of underperformance, with the result that delivered aircraft are often capable of improved performance following acceptance flight testing with only relatively slight design modifications. This inherent capacity for improvement seems to be an important determinant of the so-called "stretching" process discussed previously.

The strong historical trend has been towards aircraft with higher Reynolds numbers; vehicles have become larger and faster. This trend is slightly compensated by the offsetting trend towards higher altitude flight where the atmosphere density declines accordingly. The most recent innovations in wind tunnel testing are being included in the National Transonic Facility, which embodies both the ability to pressurize and cool the airstream and to accelerate it to sonic velocities. This raises the test Reynolds number substantially.<sup>2</sup> Velocities around Mach 1.0 are quite important for the high speed, subsonic transport aircraft since they not only approach this velocity themselves, but

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<sup>1</sup>The problems of Reynolds number flow modeling have been greatest in the transonic flow regions. Subsonic flows are critical in high angles of attack experienced during takeoff and landing, and have been addressed by the large-scale subsonic tunnels available for some time now. On the other hand, supersonic cruise simulations are quite accurately and satisfactorily addressed using small-scale modeling. However, at transonic speeds the airflow over wings becomes an extremely complicated combination of interacting flow fields. Due to the inability of extant test facilities to generate the requisite Reynolds numbers for these transonic simulations, there have been a few serious and costly surprises; for example, the C-141 and the C-5A transport aircraft. See J. L. Jones, The Transonic Reynolds Number Problem, NASA Ames, Moffett Field, CA, 1976.

<sup>2</sup>See Jones op. cit., pp. 9-13.

sectional airflow over subsonic surfaces can and do exceed the speed of sound. Figure 17 shows the various design parameters for various aircraft types which are sensitive to Reynolds number. The importance of obtaining this data at early design stages is suggested by the data in Figure 18, where devices such as supercritical airfoils and vortex diffusers which have critical transonic dynamics can have substantial impact upon the economies of subsonic transport aircraft.

To underscore the several trends and unevenness of development suggested by testing technology, we may refer to Figure 19. First we confirm that the general undeniable trend is to aircraft innovation resulting in increasing flight Reynolds numbers. Perhaps most striking is the inability of extant facilities to achieve the full Reynolds number environment for aircraft subsequent to the DC-3 generation of vehicles. Since the 1930's, tests have fallen increasingly short of requirements, and designers have accordingly had to rely increasingly upon extrapolations from available, limited facilities, and data from previously designed aircraft which have already flown. This not only creates an environment of uncertainty around certain ongoing design proceedings, but also induces designers not to deviate substantially from previous successful designs, thus attenuating the potential for radical design improvements which provide such a fertile medium for complementary, less radical technological advances which we have seen are responsible for the substantial gain in air transport productivity. This uncertainty can increase the time required for the design and development process while redundant information is collected and analyzed. This uncertainty can be reduced to some extent by rapid analysis and interpretation of the wind tunnel data by use of modern digital computer techniques. In addition, progress has been made in calculating the flow fields about arbitrary wings and

bodies in nonviscous compressible flows and that some promise exists to reduce the use of wind tunnels in the aeronautical design process<sup>1,2</sup>. Although some feel<sup>3</sup> that the large-scale digital computer could completely supplant the wind tunnel in this design process, it is too early to see if this is really true, especially in representation of the complex flow fields near a Mach number of 1.0 and slightly above or accounting for the effects of high Reynolds number flow (flow viscosity). Finally, we can see from Fig. 19 the unevenness of design within wind tunnel technology itself, since the now-being-constructed NTF represents such a large gain in capability over its predecessors with no intermediate capability facilities being constructed in the intervening years. But an excursion into this testing technology, instructive as that would be at this juncture, leads us too far afield from our central focus upon productivity increases in the air transport industry.<sup>4</sup>

Another aspect of the alpha phase of the innovation process which is being included in the initial design process is the whole dynamics of aircraft-pilot interface problem (or in other terms the provision of adequate flying qualities).<sup>5</sup> As the improved performance capabilities of new aircraft have made this interface

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<sup>1</sup>The Aerodynamic Analyses Requiring Advanced Computers, Vols I & II, A compilation of papers presented at a Conference held at Langley Research Center, Hampton, VA, March 4-6, 1975. NASA SP-347.

<sup>2</sup>Gessow, Alfred, and Morris, Dana J., A Survey of Computational Aerodynamics in the United States, NASA SP-394, Wash., D. C., 1977.

<sup>3</sup>Chapman, Dean R., Mark, Hans, and Pirtle, M. W., Computer vs. Wind Tunnels for Aerodynamic Flow Simulations, Astronautics and Aeronautics, April 1975, pp. 22-35.

<sup>4</sup>But see, for example, Miller & Sawers, op. cit., pp. 168-175, 246-250.

<sup>5</sup>Gilruth, R. R., Requirements for Satisfactory Flying Qualities of Airplanes, NACA-Washington, D. C., Rept. No. 755-1943.

increasingly critical, there has been greater stress laid upon the human engineering aspects of the design of both aircraft control, hardware and software, especially since irreversible servo-driven control surfaces have been used. Consequently, aspects of the aircraft's suitability for human control (and the effectiveness of that control) which were somewhat uncertain prior to actual test flight, can now be largely anticipated before design configurations are embodied in equipment - by the expanding use of flight simulators, for example.<sup>1&2</sup>

Much of the technological development leading to increased innovation of commercial transport aircraft originated with military vehicles, where the central innovations were first made and then transferred, with important adaptation, to commercial aircraft.<sup>3</sup> This was conspicuously the case with the development of turbojet powered vehicles. Jets with both straight and swept back wings were introduced among military fleets some years prior to their delivery to airlines in present transport configuration. However, it should be recognized that the civil and military sectors have different concerns and criteria which, in spite of considerable overlapping, impose limits to the transfer of design and innovation between them. The civil sector, for example, places great emphasis upon commercially-based considerations such as economy of cost in operation, reliability, and long useful life-- criteria which are not so overriding in the military

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<sup>1</sup>Belsley, S. E., Man Machine System Simulation for Flight Vehicles - See References, IEEE Transactions of the Prof. Tech. Group on Human Factors in Electronics, Vol. HFE-4, #1, Sept. 1963.

<sup>2</sup>Davies, D. P.: Approval of Flight Simulator Flying Qualities, Aero. Jour., July 1975, p. 281-297.

<sup>3</sup>Paulisick, J. D., R&D Contributions to Aviation Progress (RADCAP). Vol. I, Summary Rept. (Air Force Dept.) Aug. 1972, NASACR-129572, Sup. II-5.

sector, where there is an overwhelming (but not exclusive) concern with certain kinds of performance characteristics.<sup>1</sup>

When a transfer of technology takes place from the military to civil facilities, it should not be too surprising that the success of the transfer is highly dependent upon important secondary technological advances which render the military technologies economically desirable for civil utilization, thus underscoring still another unevenness in the historical development of air transport technology. The reasons for this have mostly to do with the design objectives of the users of aircraft. Whereas, for civil aircraft, all focus is upon the "bottom line" of profitability and consequently innovation which increases productivity and lower costs. This emerges as a rather secondary concern of military designers. The latter are far more interested in performance characteristics such as maneuverability, range, effective altitude, climbing and diving rates, acceleration, etc., than in how much it costs to achieve these objectives, though, ceteris paribus the cheapest configuration is of course pursued. Still, these performance characteristics, while of little value to commercial aviation, do little in the first instance to reduce operational costs and indeed are more likely to result in a deterioration of civil measures such as costs per available seat mile of operation. This no doubt goes a long way though not the whole way to explain the

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<sup>1</sup>Miller & Sawers in fact suggest that the heavy reliance upon government funds has had a seriously debilitating effect upon the airplane industry, at least in certain respects. "Lavish government spending on the products and research of the industry may have been a mixed blessing, for it may well have helped to inflate the development and production costs of airliners by accustoming manufacturers to extravagant ways (when firms could build new and elaborate research laboratories to prove to the government that they were able to carry out its research contracts, this extravagance was genuine enough). Engineers accustomed to such circumstances might find it difficult to place the same emphasis on the cost of their work as their poverty-stricken predecessors did in the 1930's. Dependence on the government has thus been a mixed blessing for the aircraft industry; it has been given the jet engine, and lavished with other gifts, but they have weakened the commercial and engineering instincts which helped the industry to take the first great step forward in airlines design in the 1930's. Its second leap forward might have been a bigger one if it had been less dependent on the government, but it could do nothing without the government's gifts. That is the paradox of the jet airliner's origins." Miller & Sawers, op. cit., p. 157.

intervening time between adoption of innovation by military vehicles and the eventual introduction into civil transport aircraft, as in the decade that separated jet tactical vehicles from the Boeing 707. For example, the first economically viable jet engines for civil transport used about 0.9 pounds of fuel per hour-pound of thrust, and this has subsequently improved to around 0.6 pounds of fuel per hour-pound of thrust (see Fig. 20). In contrast, the J-35 engines used in the military B-47 bombers, which preceded the introduction of civil jet aircraft, required about 1.075 pounds of fuel per hour-pound of thrust as well as suffering from substantially less installed thrust. We have already noted the differences in maintenance philosophies and their economic consequences.

We can achieve some idea of the quantitative dimension of the process from Figures 21a through 21i, which provide information upon the length of time separating the availability of innovation from the incorporation in civil transport airplanes.<sup>1,2</sup> Many of these innovations originated in the process of designing and building military aircraft, though of course many others did not. However, what uniformly impedes their application is their anticipated or realized failure to improve the productivity profiles of civil aircraft. Although many of these technological innovations have found their way into civil application, no doubt because they become economically desirable when used in conjunction with subsequently developed complementary technologies, many of them remain on the shelf after more than 30 years of technical feasibility. Of the total sample of 550 advances, only 312, or less than 60% have found their way into application. Broken down by type of technology, this ranges from a low of 46% of aerodynamic innovation achieving implementation to a high of 84% of technological advances in avionics being economically desirable for implementation on civil vehicles.

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<sup>1</sup>Joint Department of Transportation-NASA Civil Aviation R&D Policy Study TST-30, A Historical Study of the Benefits Derived from Application of Technical Advances to Civil Aviation, 1971, Vol. II. Appendix B.

<sup>2</sup>See also Miller & Sawers, p. 226.

Of course, this is not to say that innovations which have been adopted by civil aviation are superfluous to the advancement of this segment of the aircraft industry. Rather, our earlier arguments of the unevenness of technological and productivity development within the industry suggests that it is quite likely that these now dormant technologies will eventually be embodied by civil air transport vehicles.

However, before this is possible it is necessary that complementary technologies be developed which render the extant potential technologies economically desirable as well as technologically feasible.

We have placed great stress in this paper upon the role of complementarities in the operation of aircraft and have focused in particular upon the interrelations between the engine and the airframe, emphasizing in particular how improvements in one have required improvements in the other. If time and space permitted we could show how similar relationships of complementarity have played a critical role elsewhere. As Walter Vincenti of Stanford University has shown in an unpublished article, in the earlier history of the industry there was an intimate relationship between gradual and often quite inconspicuous improvements in the design of propellers and the subsequent need to modify the design of the airframe.<sup>1</sup> There was a continuous and reciprocal interaction between improvements in fuels and new reciprocating engine design. The requirements for the engine in the form of increased performance and increased reliability improvements have demanded improved fuels for their full exploitation, and the availability of these improved fuels have on the other hand made it evident that existing engines could be further extended to take advantage of the full capabilities of the new fuel. Thus, there has been an interplay between the reciprocating engine builders and suppliers of fuel,<sup>2</sup> the outcome of

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<sup>1</sup>Walter Vincenti, "Air-Propeller Tests of W. F. Durand and E. P. Lesley: A Case Study in Technological Methodology," unpublished manuscript, 1976, pp. 6-7.

<sup>2</sup>See Robert Schlaifer and S. D. Heron, Development of Aircraft Engines and Fuels Cambridge: Division of Research, Graduate School of Business Administration Harvard University, 1950, pp. 552, 558-9.



which has been progressive improvement through the utilization of each advance in engine and fuel performance.<sup>1</sup>

For gas turbine engines, the interaction between fuel and output are not as dramatic; in fact, the gas turbine, once running, is very forgiving about the fuel type used. The increases in jet engine output are generally associated with improved compressor design and improved turbine materials to allow higher turbine inlet temperature operation. Further thrust increases and reductions in fuel consumption are brought about by introduction of turbo fan engines, wherein increasingly larger amounts of compressor air by-pass the turbine and increase thrust. These progressions are shown on Fig. 20.

The role of metallurgical and, more broadly, materials improvements has been neglected in this paper, but such improvements have been fundamental to the growing progress of aircraft. In this respect, technological progress in aviation has been heavily dependent upon technological improvements elsewhere. In particular, the development of new, high performance alloys has been critical in the enhanced performance capabilities of both the engine and the airframe. In this respect, therefore, an appreciation of the sources of productivity growth in aircraft requires that we look beyond that industry alone and examine the role of interindustry relationships. Such interindustry interdependencies have by no means been confined to the aircraft industry. Rather, they are becoming increasingly characteristic of the "high technology" sectors of the economy. The need for new metallurgical inputs in aviation provided the inducement for technological improvements which subsequently turned out to be useful in many places other than aviation. Moreover, this has proved to be a two-way

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<sup>1</sup>Boeing Commercial Airplane Company, op. cit., p. 3 and Fig. 4. Also Schalifer and Heron, op. cit., especially Part II, Ch. 7.

street. Materials improvements originating outside the industry often proved to be of great value in the production of aircraft, but materials developed originally in the aircraft industry also proved to be valuable to other industries. What has been asserted with respect to materials here is true of a wider range of devices and techniques (See Figs. 22 & 23 for an example of the types of complementaries. These tables are nowhere complete.).<sup>1</sup> Similar statements could be made with respect to a whole range of electronic devices and techniques in recent years.

One particularly significant aspect of an investigation of these complementary technologies is the introduction and explanation of the notion of cost reductions through "learning by using" in the air transport industry. Indeed, this is the key insight for penetrating the unfolding of a diverse set of technological advances, from the immediately observable stretching of the vehicles to the considerably less obvious but no less significant cost reduction gains achieved in the aircraft maintenance shops. The richness of the explanatory power of this learning-by-using category in this particular industry, moreover, may be very useful for understanding the origins of cost reduction improvement with other high technology industries.

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<sup>1</sup>Boeing Commercial Airplane Company, op. cit., p. 3 and Fig. 4.

## CONCLUDING REMARKS

The air transport industry of the U.S. and the world has expanded because of the increases in utility, productivity and reduced cost to the user, and the stimulation afforded, at least in the U.S., by direct government subsidy to the airline operators at the outset. The utility of the aircraft has resulted in decreased block times, increased ranges, increased comfort (flight at higher altitudes resulting in smoother flights; i.e., over the weather) and closer adherence to schedule. The productivity of the aircraft; that is, the ability to carry more passengers per plane faster over the route ( $\text{seats} \times V_c$ ) has increased with most of the new aircraft introduced and with every aircraft stretch. Along with this productivity increase has come a reduction in direct operating cost per seat mile, increased reliability, and increases in useable life of the aircraft. In addition, the air transport system has gone out of its way to entice and accommodate passengers.

The technology to enable the aircraft manufacturers and the airlines to affect these advances has been put together in different ways by the different manufacturers and as one would expect, with different end results--yet with some degree of similarity. A cursory examination of the way the industry developed in a technological sense indicates that aircraft development comes in waves, each wave encompassing several new technological advances while retaining the best of the old ones. A more careful examination of these waves of progress shows that they can be readily interpreted in terms of the alpha and beta phases proposed by Enos. The alpha phases are correlated with the introduction of new aircraft generations into service, the beta phases with the development of these generations to improve both the productivity ( $AS \times V_c$ ) and the direct operating costs of each successive aircraft development. Following the mastery of the use of smooth stressed skin structural techniques (semimonoque structures) in

the early 1930's by the American aircraft industry, coupled with fundamental work by the NACA on engine cowl design and optimum engine placement in the late 20's, the basic configurations have changed very little. Throughout the years to follow, however, improvements in engine systems, aerodynamic modifications and refinements (optimized airfoil profiles, swept wings and powerful leading- and trailing-edge flaps) as well as structural design and manufacturing improvements and new materials have enabled advances in productivity and concurrent reductions in operating cost to be achieved. The reduction in operating cost for specific aircraft is shown to be significant as experience with its operation is gathered; also, improvement in specific configurations are very powerful in reducing operating costs by reducing airframe drag and by installation of more fuel efficient engines. Along with this improvement in operating cost, there is increased productivity due to increasing the passenger capacity by lengthening the fuselage (stretching).

The engine maintenance scene has been treated in a similar fashion to show that gains are achieved by introduction of successive generations of engines and careful control of maintenance requirements and costs. Further improvements through reductions of structural weights, basic drag (by airfoil modifications and active controls), and engine fuel consumption, as well as noise reduction, all tend to provide the basic technology for the next generation of transports. As history has shown, the form of these future transports will be decided by the market forces as well as the technological state of the art at the time the decision is made to proceed with a new airplane.

TABLE I TECHNOLOGICAL PROGRESS PHASES, FROM ENOS<sup>1</sup>

ALPHA PHASE

- o Invention,
- o Succeeding development in both laboratory and pilot operations, and finally
- o Installation or production in the first commercial plant. At the end of the alpha phase it is in competition with the product of the existing process.

BETA PHASE

Improvement of the innovation, and can be of three types

- o Construction of larger units to take advantage of inherent economies of scale.
- o The adoption of ancillary advances by other industries.
- o The increase in operating skill or know how.

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<sup>1</sup> J. L. Enos, P. 317, *Inventions & Innovation in the Petroleum Refining Industry in the Rate and Direction of Inventive Activity*, Princeton University Press, 1962.

AIRCRAFT \ ADVANCE	A/C RADIALS	BIPLANE	MULTI ENGINE	CANTILEVER WING	ALL METAL STRESS SKIN STRUCTURE	COWLED ENGINE	LOAD CARRY SKIN	ENGINE ON WING LEADING EDGE	RETRACTABLE LANDING GEAR	FLAPS	CONTROLLABLE PITCH PROP.	ENGINE SUPERCHARGES	CABIN SUPERCHARGES	TRICYCLE LANDING GEAR	COMPOUND ENGINE	TURBO PROP.	TURBO JET	SWEPT BACK WINGS	RIP STOP STRUCTURE	TURBO FAN ENGINE	LEADING EDGE PROTECTION	HIGH BY PASS RATIO	AUTO PILOT	IFR INSTRUMENTS
BOEING 80-A	✓	✓	✓																					
FORD TRIMOTOR	✓		✓	✓	✓																			
BOEING 80-B	✓	✓	✓			✓																		
BOEING 247	✓		✓	✓	✓	1/2	✓	✓	✓															✓
DC-3/L-10	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓												✓	✓
DC-4	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓									✓	✓
STRATOLINER	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓										✓	✓
CONSTELLATION DC-6, 240, 202, STRATO CRUISER	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					✓				✓	✓
DC-7/1049	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				✓				✓	✓
VISCOUNT/ELECTRA			✓	✓	✓		✓	✓	✓	✓	✓		✓	✓		✓			?				✓	✓
COMET			✓	✓	✓		✓		✓	✓	✓	✓	✓	✓			✓	1/2	—				✓	✓
707/DC-8 TJ			✓	✓	✓		✓		✓	✓			✓	✓			✓	✓	✓				✓	✓
707/DC-8/720 TF			✓	✓	✓		✓		✓	✓			✓	✓				✓	✓	✓	✓		✓	✓
727/DC-9/737			✓	✓	✓		✓		✓	✓			✓	✓				✓	✓	✓	✓		✓	✓
747/DC-10/1011			✓	✓	✓		✓		✓	✓			✓	✓				✓	✓	✓	✓	✓	✓	✓

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TABLE II - TECHNOLOGICAL ADVANCES IN TRANSPORT AIRCRAFT

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TABLE III SUGGESTED ALPHA-BETA PHASES - US AIR TRANSPORT SYSTEM AIRCRAFT

PHASE	CHANGE	DESCRIPTION OF AIRCRAFT TYPES AND IDENTIFYING CHARACTERISTICS	A/C DESIGNATION
BEGINNING		2-3 engine biplanes-fabric covered	Boeing 80A, 80B
		3 engine high wing monoplane, solid wing surface, either plywood or metal	Fokker Ford
	NACA cowl introduced		
α	Increased aerodynamic and structural efficiency; increased productivity, lower operating cost	2-engine low wing monoplane, smooth stressed skin-all metal structure with controllable pitch propeller, and retractable ldg gear	247
β	Increased size, speed (productivity) lower operating cost increased passenger comfort	constant RPM propeller, deicing-mechanical, pressurized cabin, exhaust heat deicing, 4-engine low wing monoplane, tri-cycle landing gear, flaps	DC-2, L-10 DC3, L12, L14 M 202 404 220 440 DC 4
α	Pressurized cabin, larger size-increased payload high-altitude operations, increased ride comfort, increased productivity, lower operating cost	4-engine low wing all metal monoplane with pressurized cabin	307
β	Use of turbo prop. increased speed -productivity increased size	larger aircraft, longer range increased passenger capacity increased speed compound engine, more powerful flaps	DC-6, 6B 049 DC-72 049 B 377 1049 Viscount 1049C L-188

CHARACTERISTICS OF A/C TYPES TABLE III (cont.)

PHASE	CHANGE		
α	turbojet engine, increased size, <u>speed</u> and productivity, higher altitude operation-ride comfort	4-engine turbojet moderate wing sweep	Comet I
β	Increased size, increased wing sweep, longer range, increased productivity, lower cost operation,	2-engine turbojet moderate sweep	Caravelle
	Broader market served more optimum size for shorter haul markets.	4-engine turbojet, 35° sweep, spoiler lateral control	707-DC8 720 880 990
		3-engine turbo fan- medium range, leading edge flaps	727
		2-engine turbo fan medium range	DC9 BAC-111
α	High Bypass ratio turbo-fan increased size and productivity	4-engine, high pass ratio turbo fan wide body	747
	lower operating cost		
β	refine aerodynamics	3-engine high bypass ratio turbo fan-wide body	DC-10
	lower direct operating cost		1011



TABLE IV-COMPARISON OF PRODUCTIVITY, DIRECT OPERATING COSTS  
AND CRUISING SPEEDS FOR BEGINNING OF ALPHA PHASE SINCE 1940

	YEAR	PRODUCTIVITY CHANGE, AS x V <sub>C</sub>		DOC COST CHANGE, CENTS/SM		CRUISE SPEED, MPH		
		actual	increase	actual	reduction	actual	increase	
DC-3 Gen to 307 Gen	1940	9400 - 3700	5700 (150%)	4.78 - 3.23	+ 1.55	200 - 180	+20	
307 Gen to Comet	1952	9400 - 21500	12,100 (129%)	3.2 - 4.23	- 1.03	490 - 200	+290	
307 Gen to (707,TJ) Gen	1959	9400 - 73000	66,600 (726%)	3.2 - 1.72	+ 1.48	580 - 200	+380	Comet only had speed and comfort of flight to sell, not increased productivity or reduced costs - See Fig. 5.
T Fan narrow body (707) to T Fan wide body (747)	1970	73000 to 218,000	145,000 (197%)	1.015 - 715	+ .300	590 - 580	+10	

TABLE V. BETA PHASE EFFECTS ON PRODUCTIVITY, DIRECT OPERATING  
COSTS AND CRUISING SPEEDS FOR AMERICAN TRANSPORT AIRCRAFT SINCE 1933

	YEAR	Productivity Change AS x Vc		DOC Cost Change Cents/SM		Cruise Speed MPH		Remarks
		ACTUAL	INCREASE	ACTUAL	INCREASE	ACTUAL	INCREASE	
2-engine series 247-440	1933-1955	1800 - 14600	12,800 (710%)	7.87	-5.60	170 to 280	+110	note later version of 2-engine machine were pressurized, also large jump is from 1940 to 1947 time period where technology accumulation during WW II was utilized.
4-engine series 307- 1049C/DC7C	1952 to 1964	9400 - 25200	15,800 (169%)	3.20 to 1.88	-1.32	200 to 310	+110	
4-engine turbo jet series								
Begin W/Comet	1952 to 1964	21500 to 73000	+51,500 (240%)	4.25 to 1.13	-3.12	490 to 610	120	
Begin W/707	1959 to 1964	73,000 60,500	-12,500 (-17.1%)	1.70 1.13	-.57	580 to 610	30	

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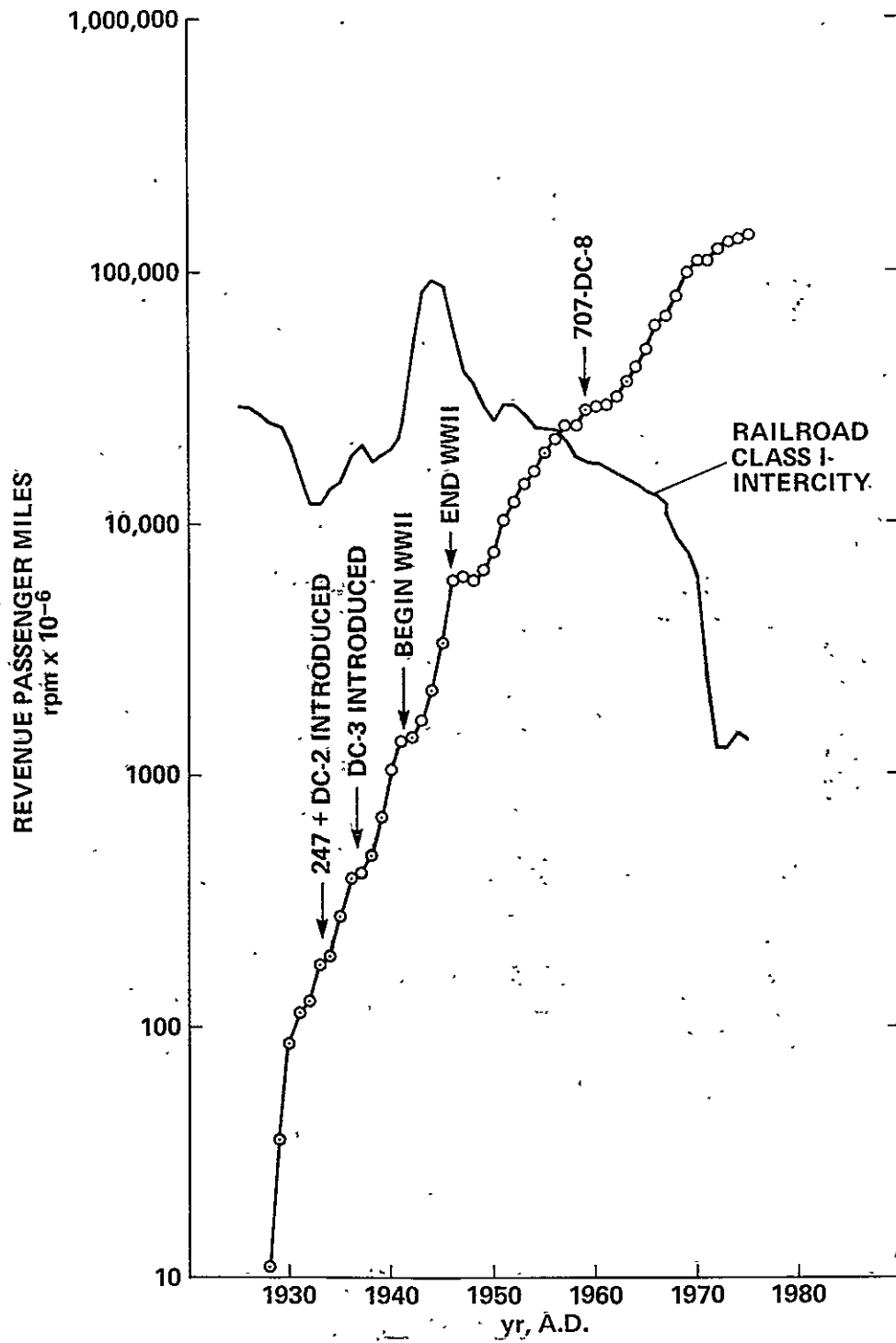


Figure 1.—Growth of airline revenue passenger miles — U.S. domestic.

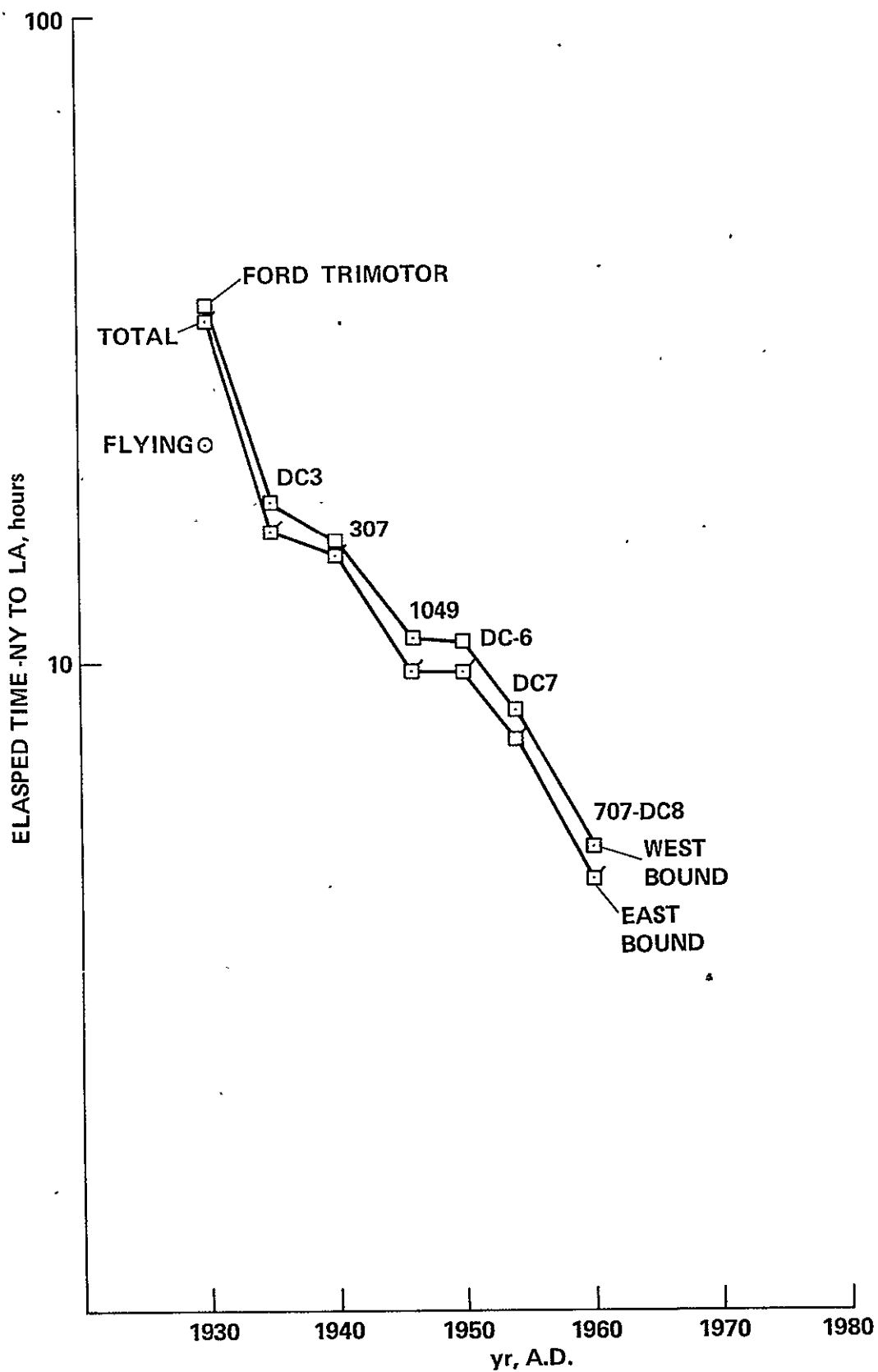


Figure 2.— Coast to coast time — scheduled airlines (representative figures).

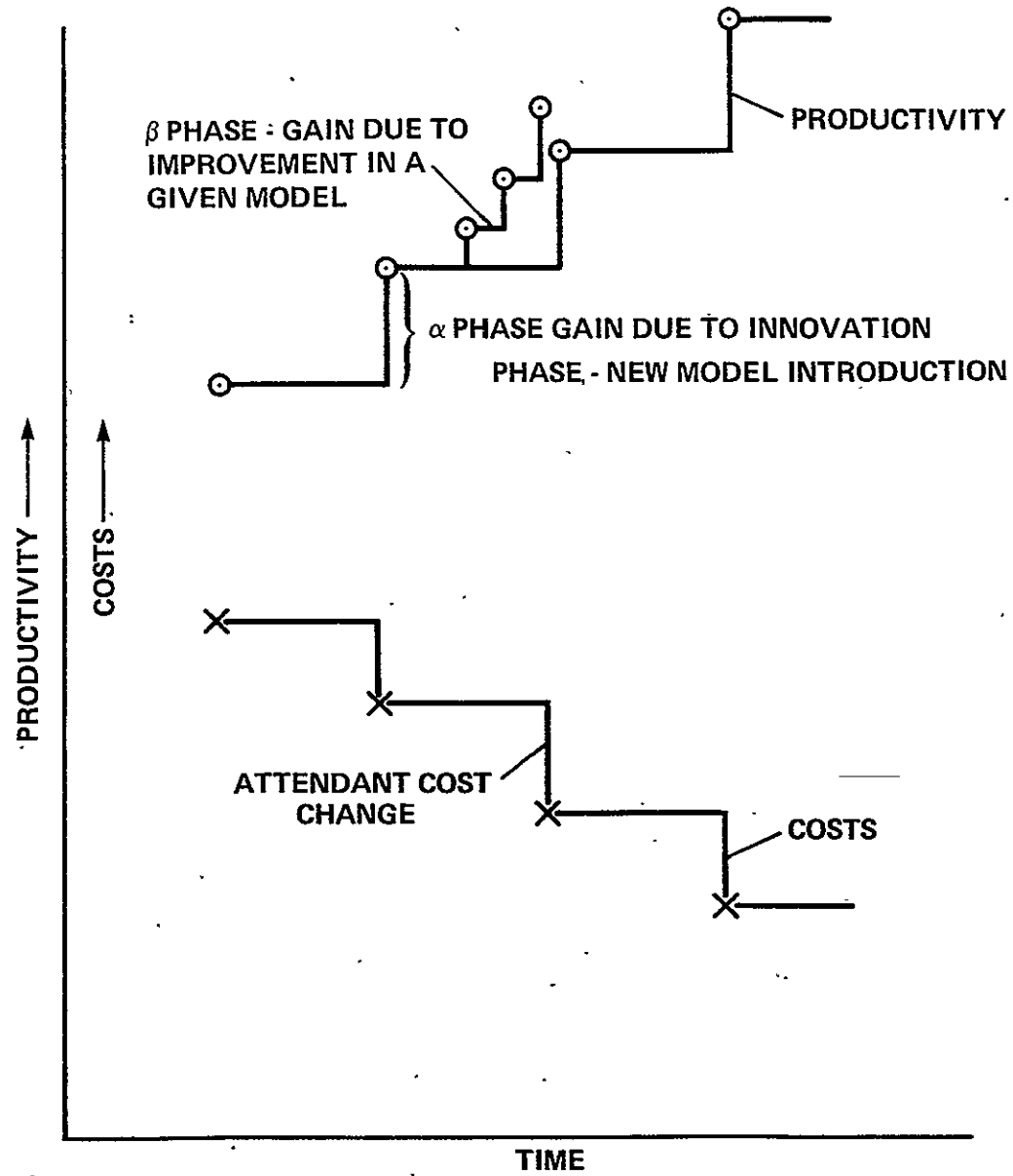


Figure 3.—Illustration of  $\alpha$  and  $\beta$  phases of the innovative process.

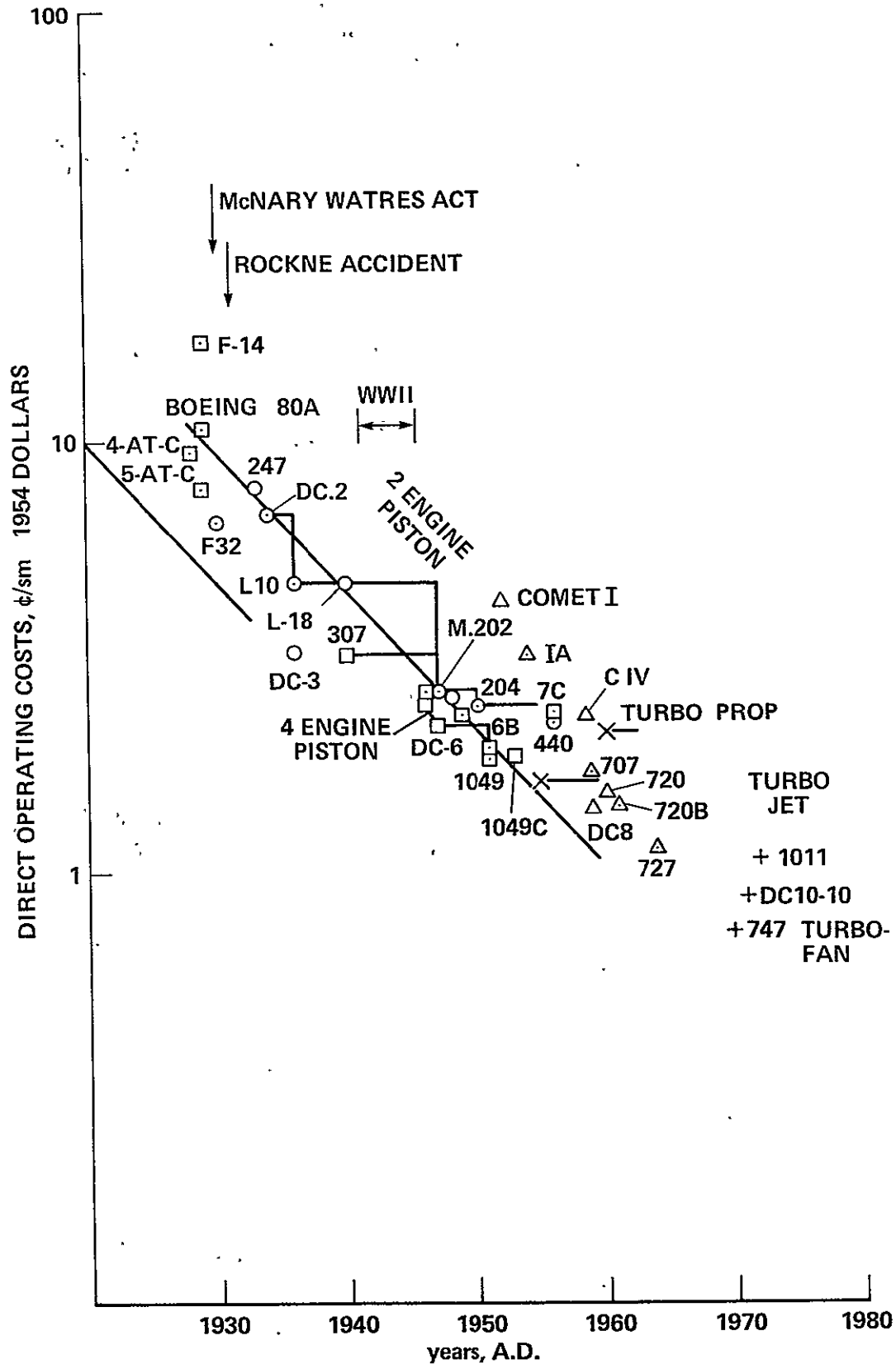


Figure 4.— Direct operating costs of multiengine American transports — first year of operation (1954 dollars).

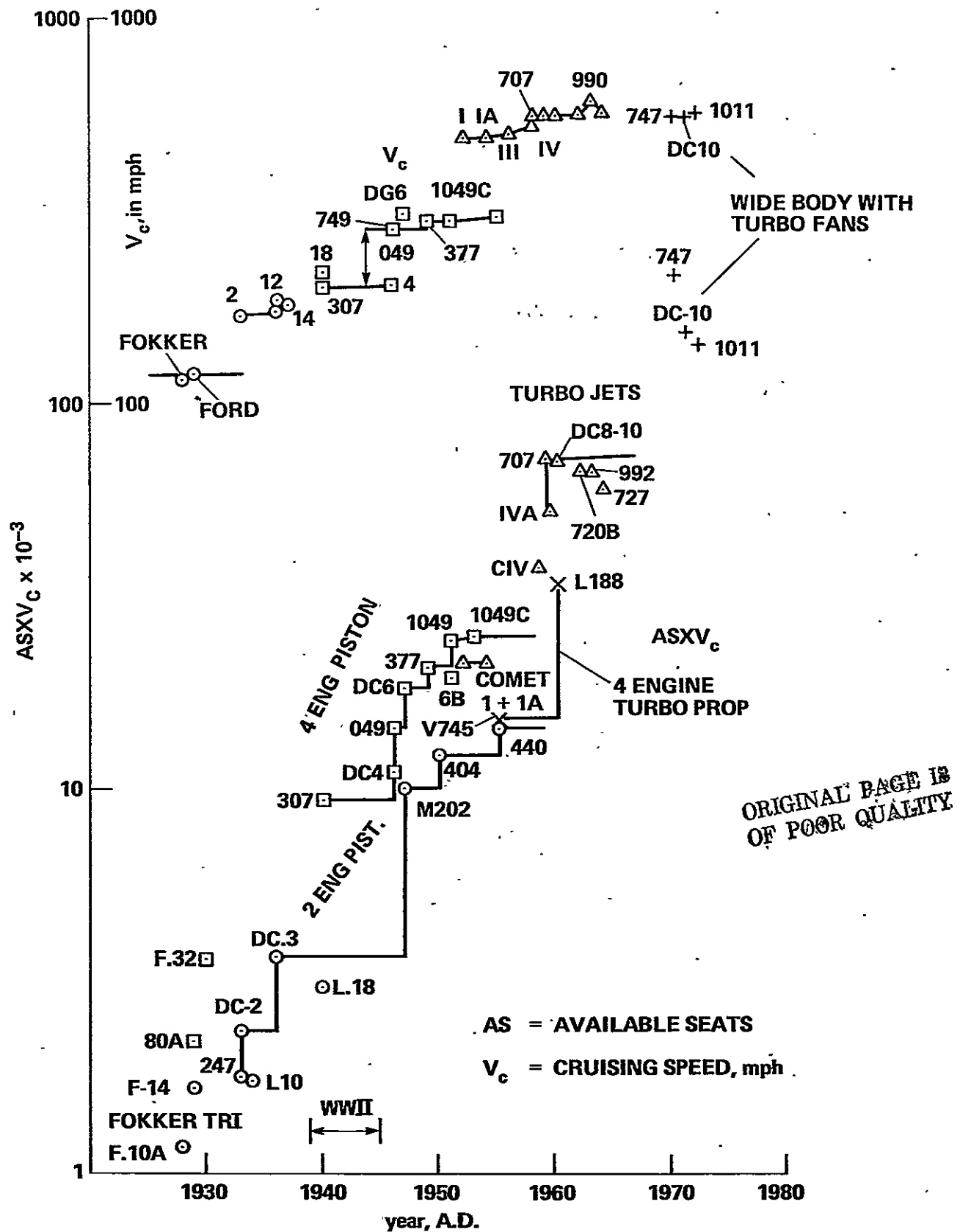
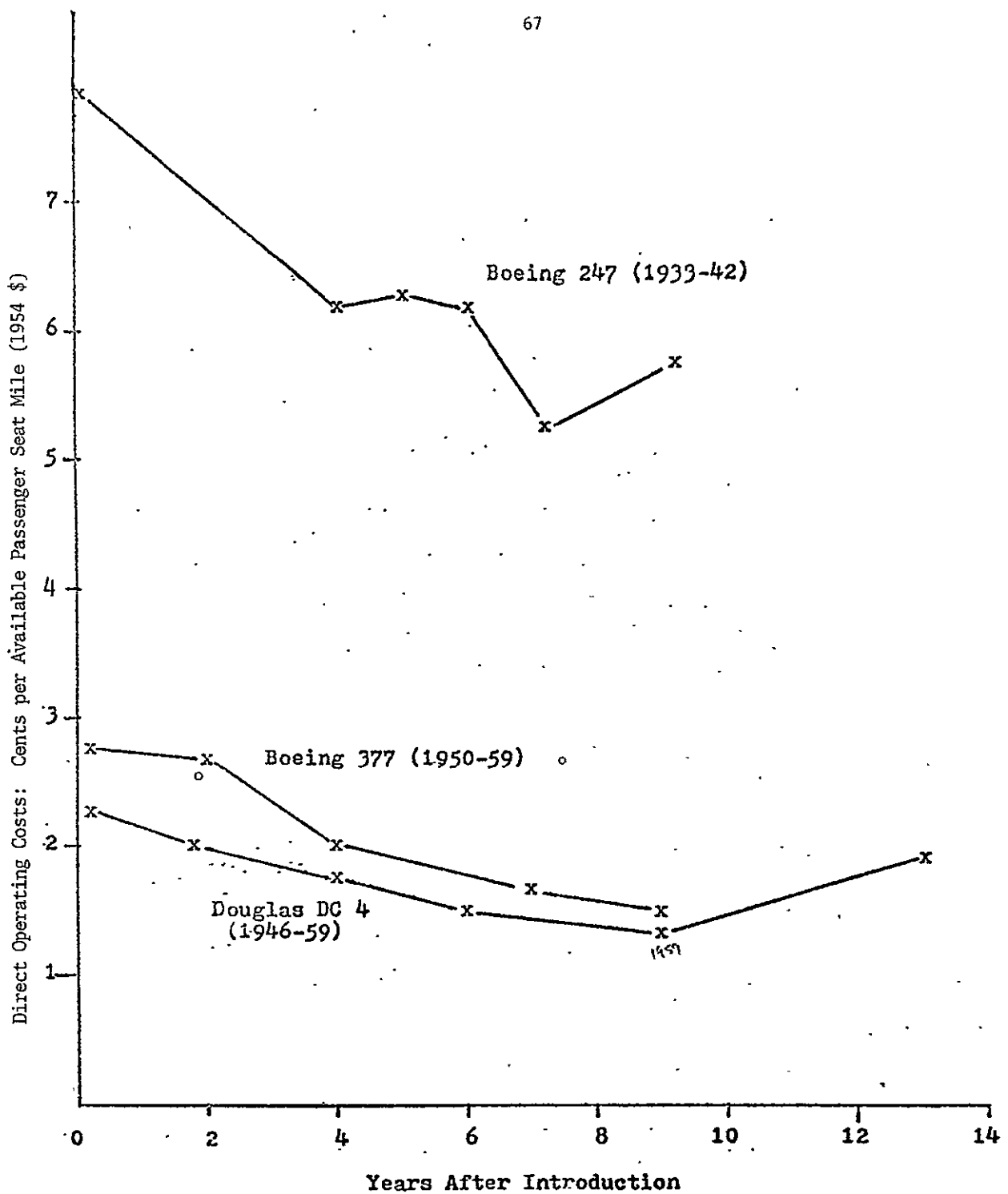


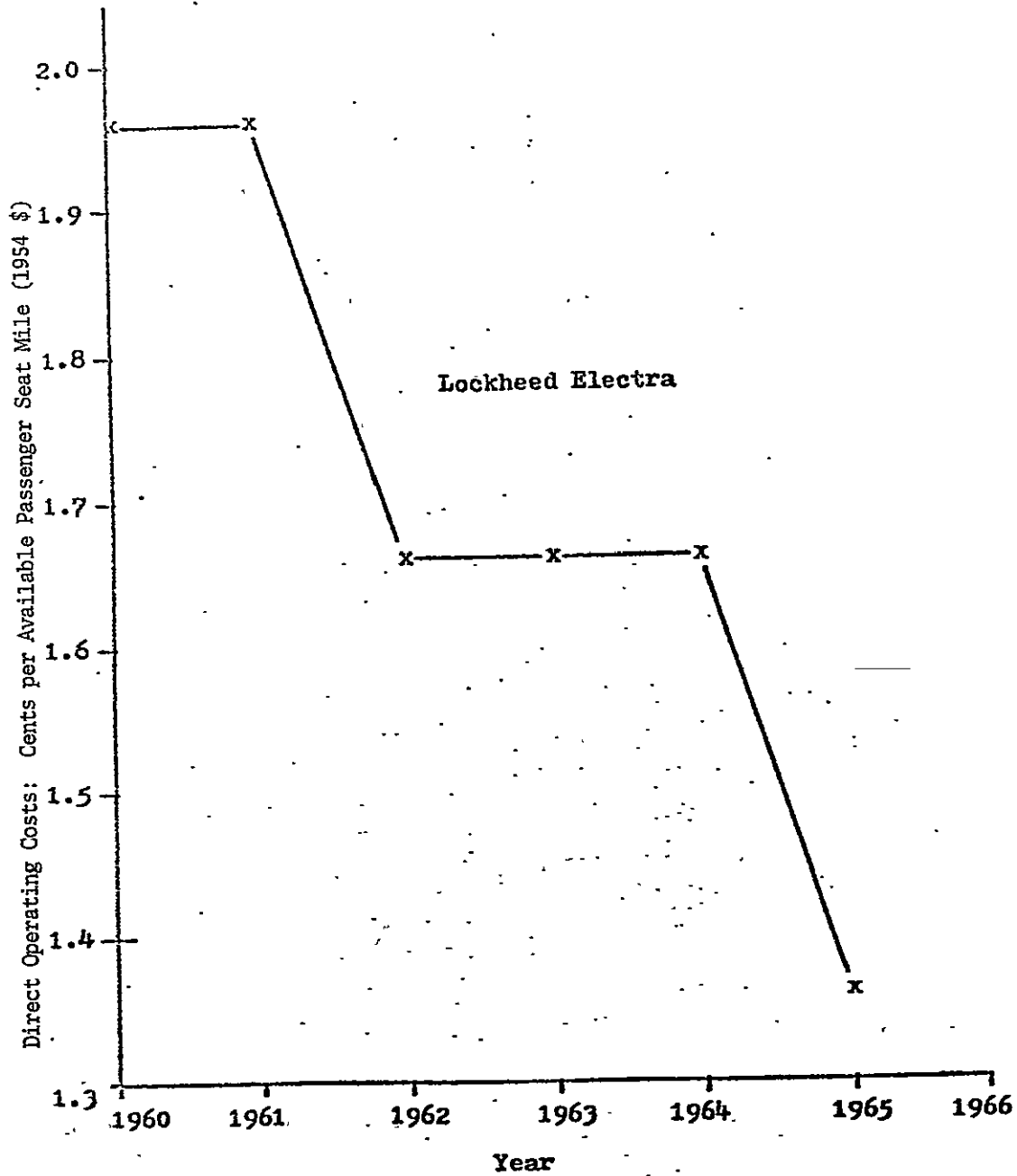
Figure 5.— Passenger carrying productivity as expressed by  $AS \times V_c$  multi-engine American transports.



Source: Phillips, op. cit. pp. 38-39

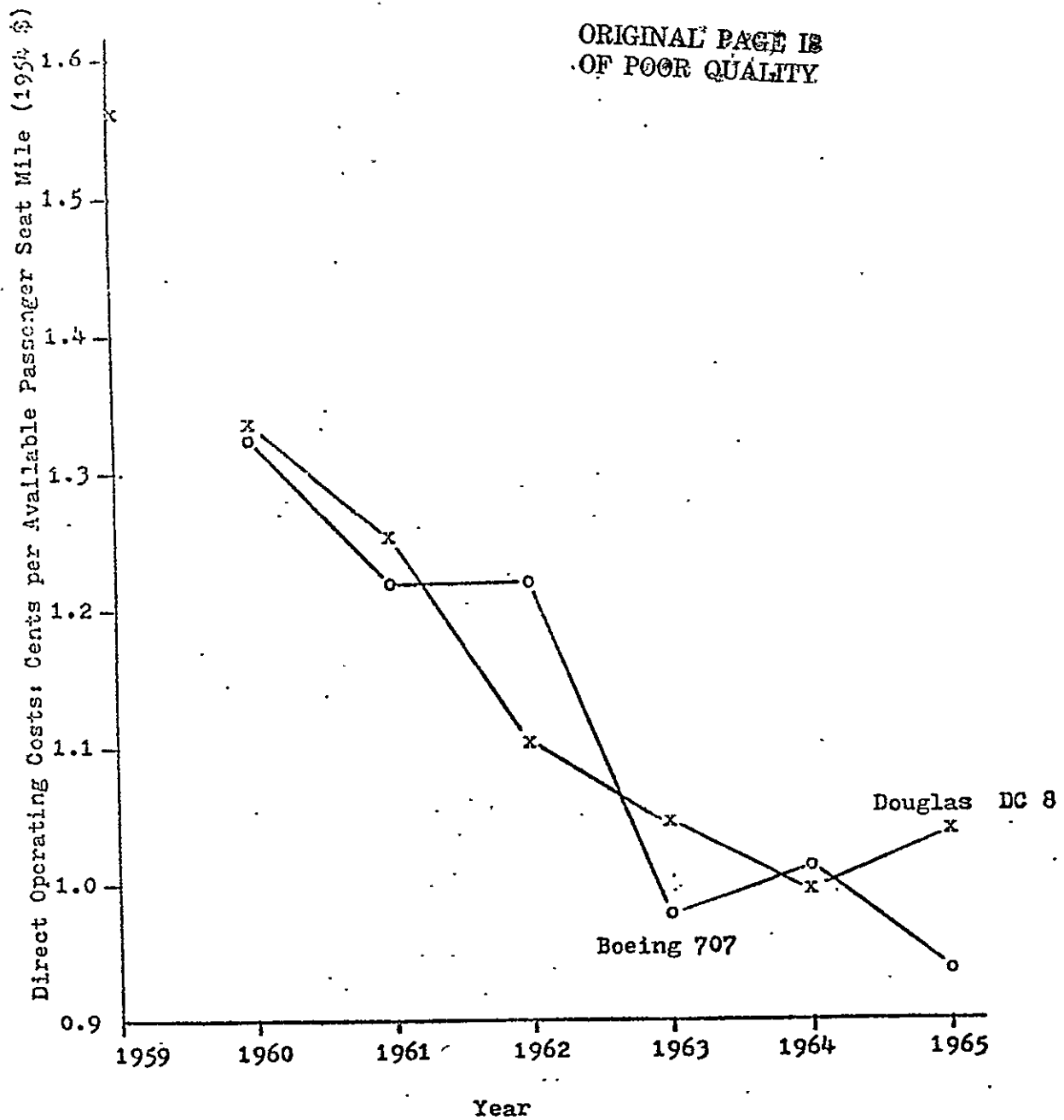
Figure 6.-- Beta phase direct operating cost reduction of particular piston aircraft.





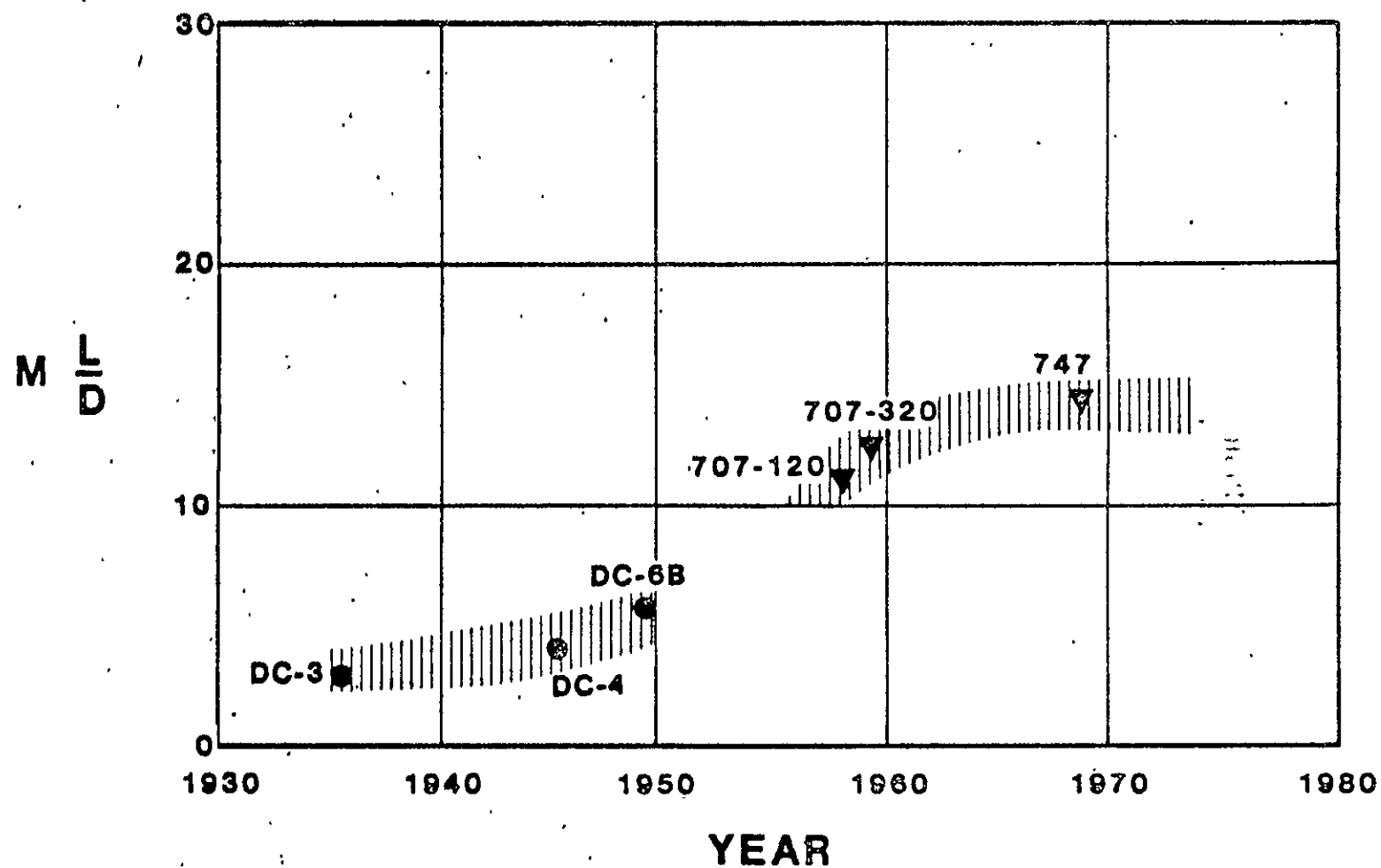
Source: Phillips, op. cit. p. 41

Figure 7.— Beta phase direct operating cost reduction for a turboprop aircraft.



Source: Phillips, op. cit. pp. 40-41

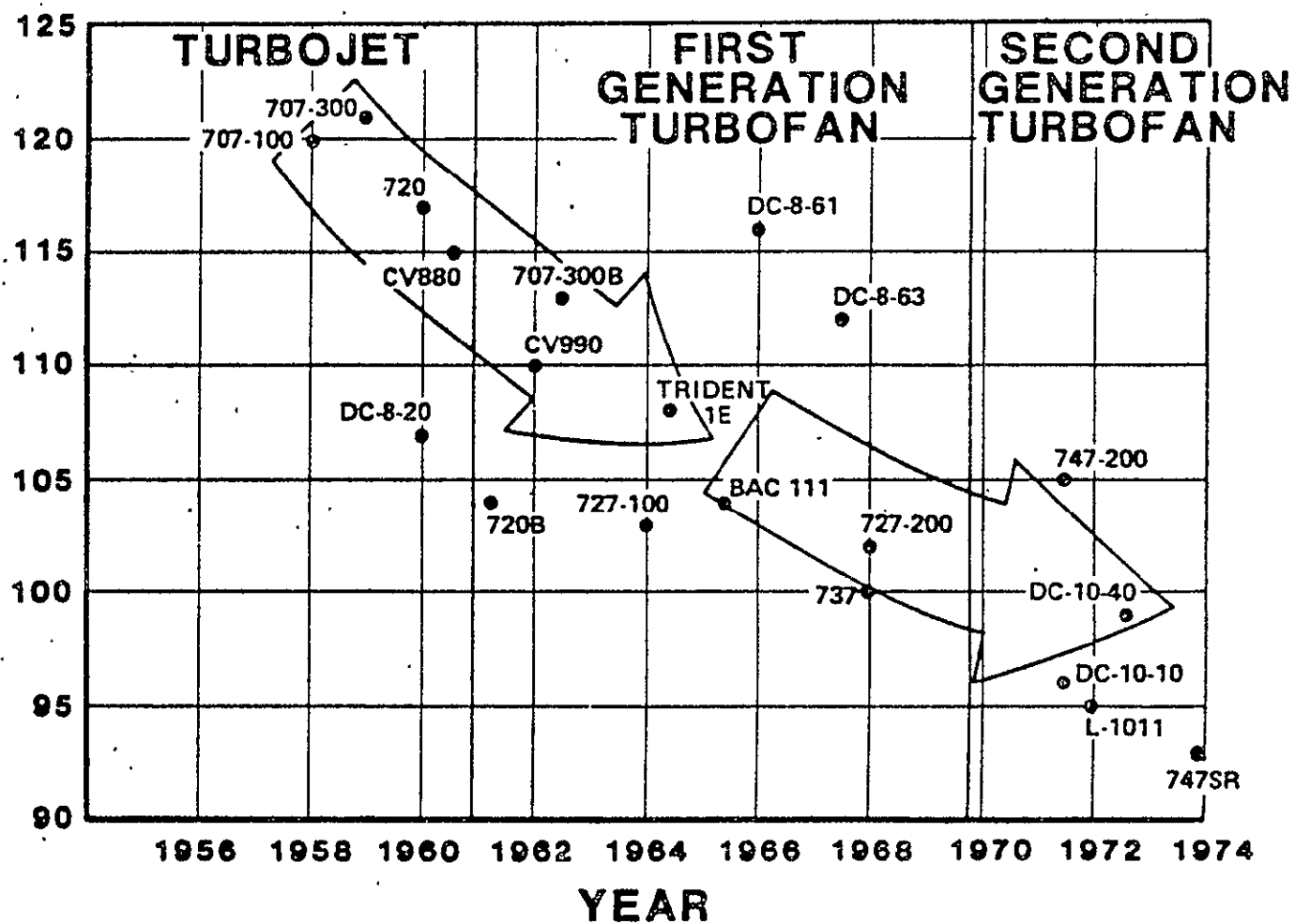
Figure 8.- Beta phase direct operating cost reduction for two specific turbojet aircraft.



Source: Boeing Commercial Aircraft Company, op. cit. Figure 6

Figure 9.- Aerodynamic efficiency trends.

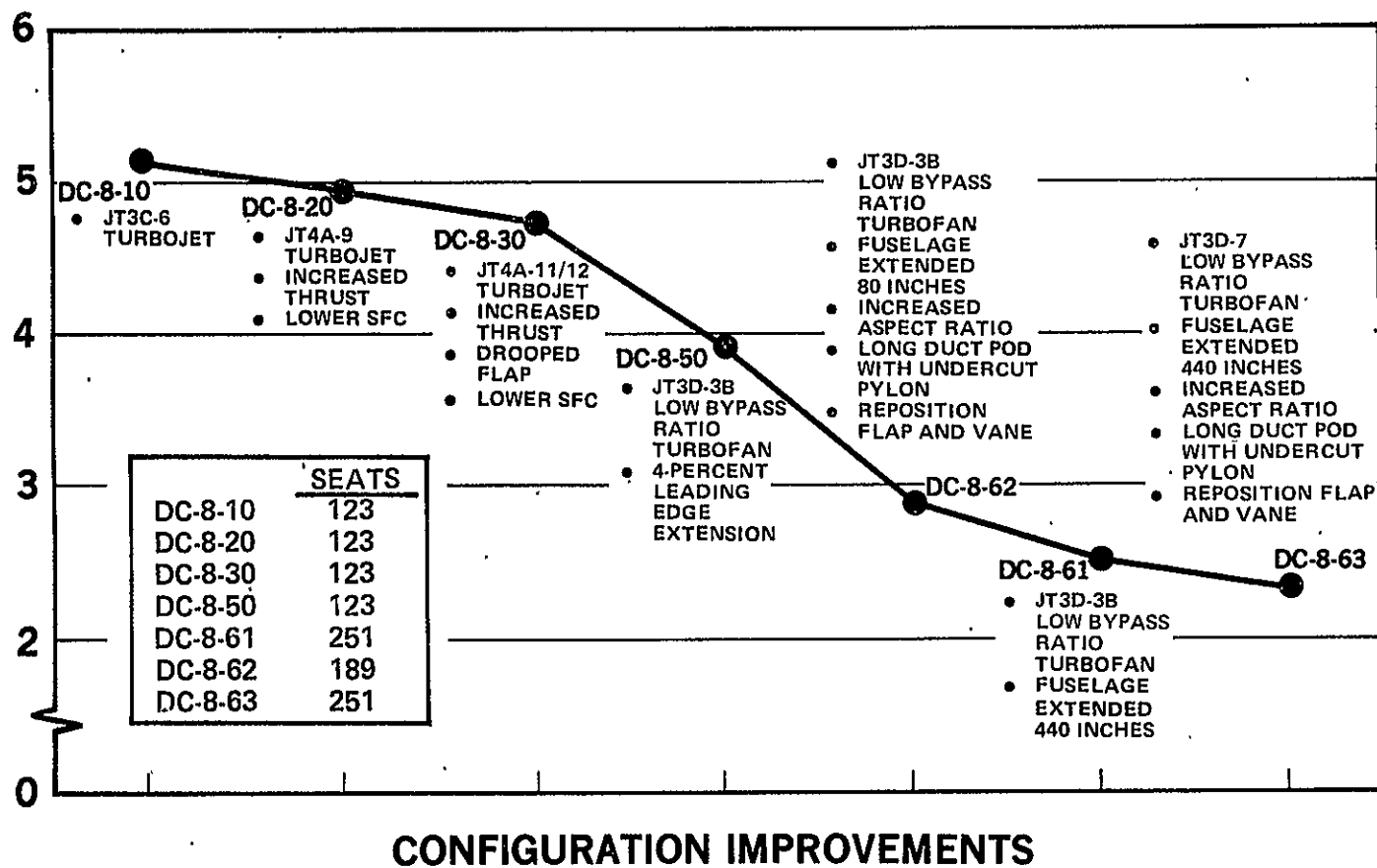
EPNL-  
EPNdB



Source: Boeing Commercial Airplane Company, op. cit. Figure 7

Figure 10.- Engine noise time trends.

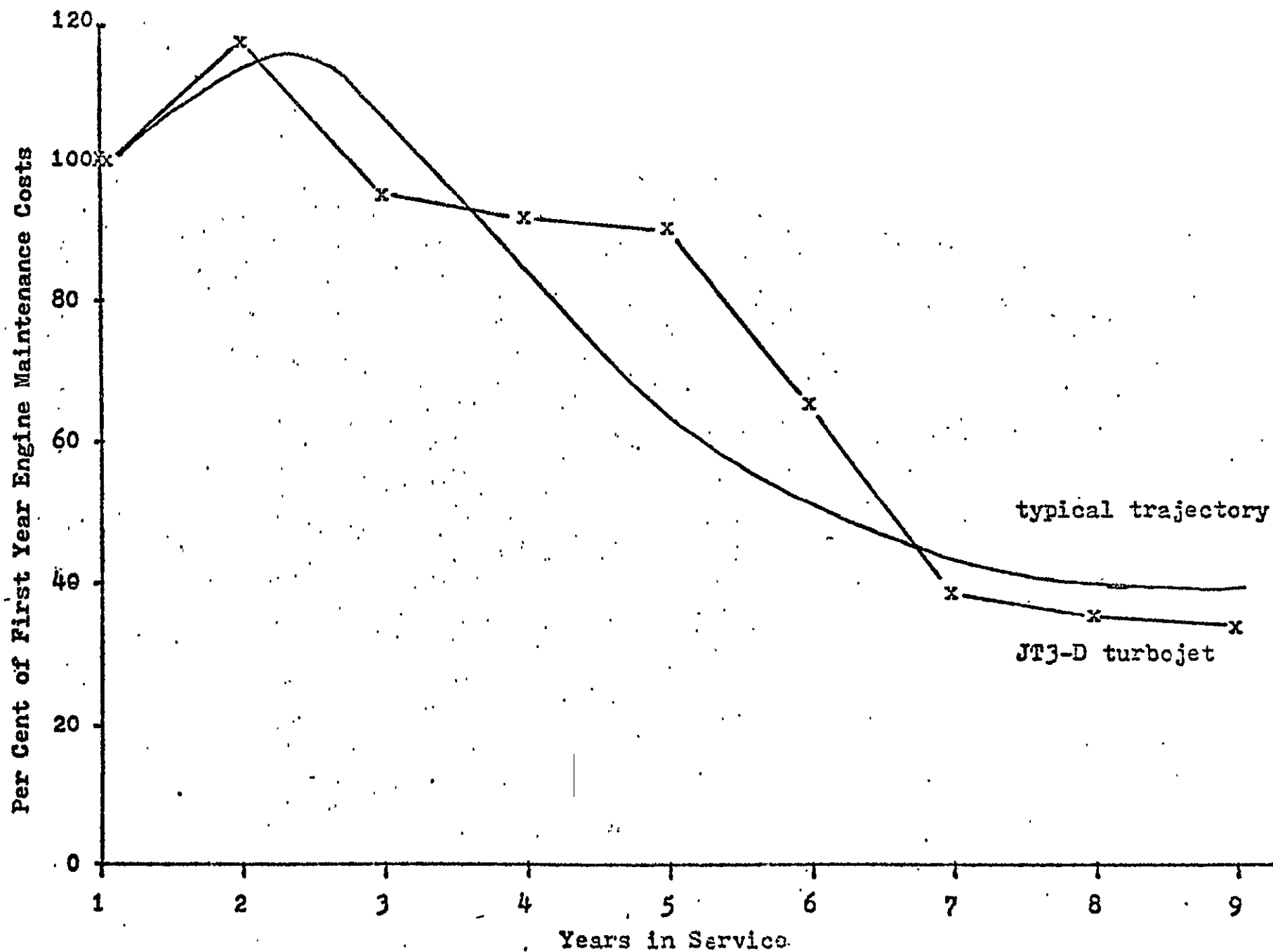
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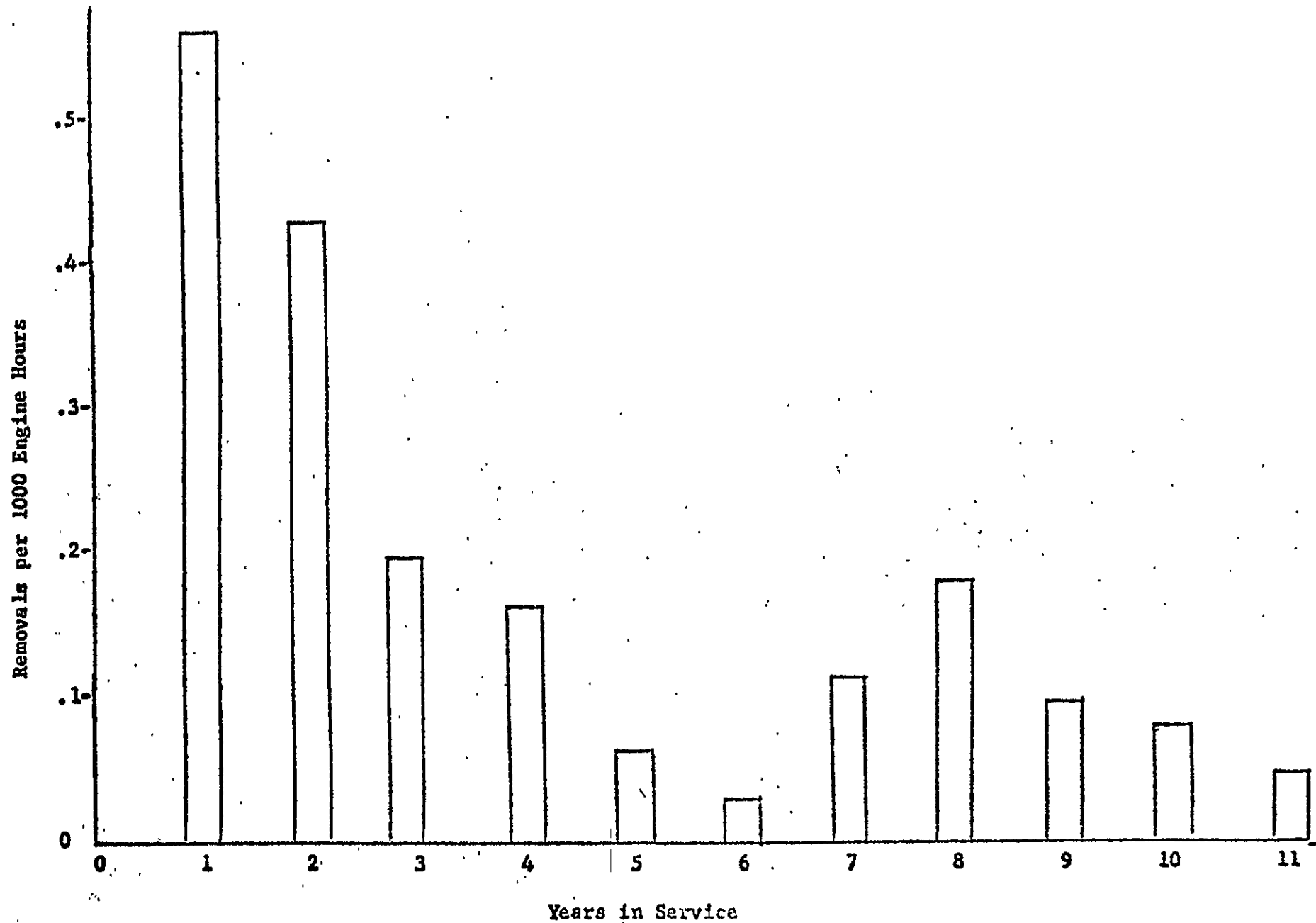
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Figure 11.- DC-8 comparative energy consumption — range: 2000 n. mi.



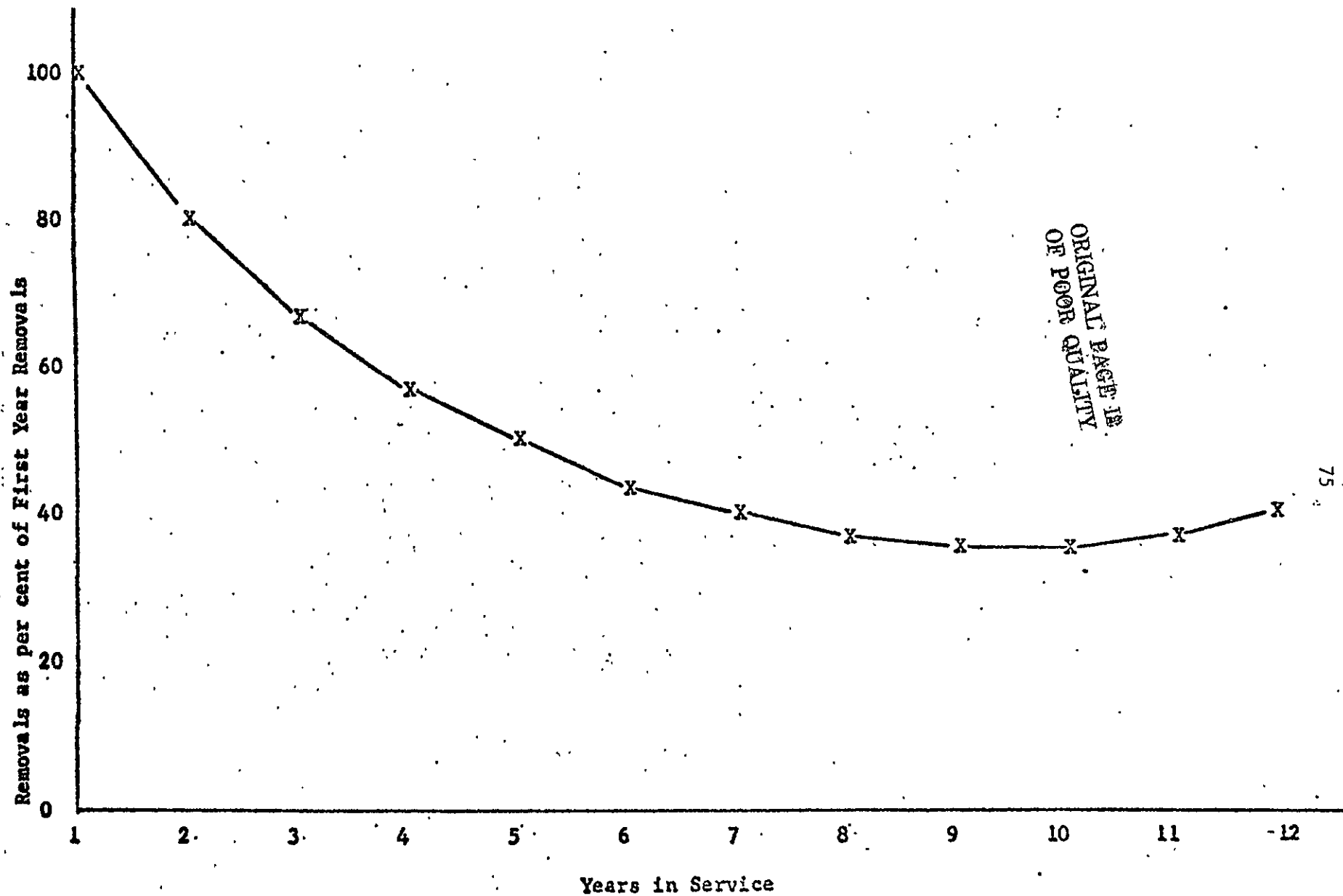
Source: NASA CR-134645 op. cit.

Figure 12.- Engine maintenance expense.



source: Sallee, C. P. Economic Effects of Propulsion Systems Technology on Existing and Future Aircraft  
American Airlines, New York, 1974, p. 40

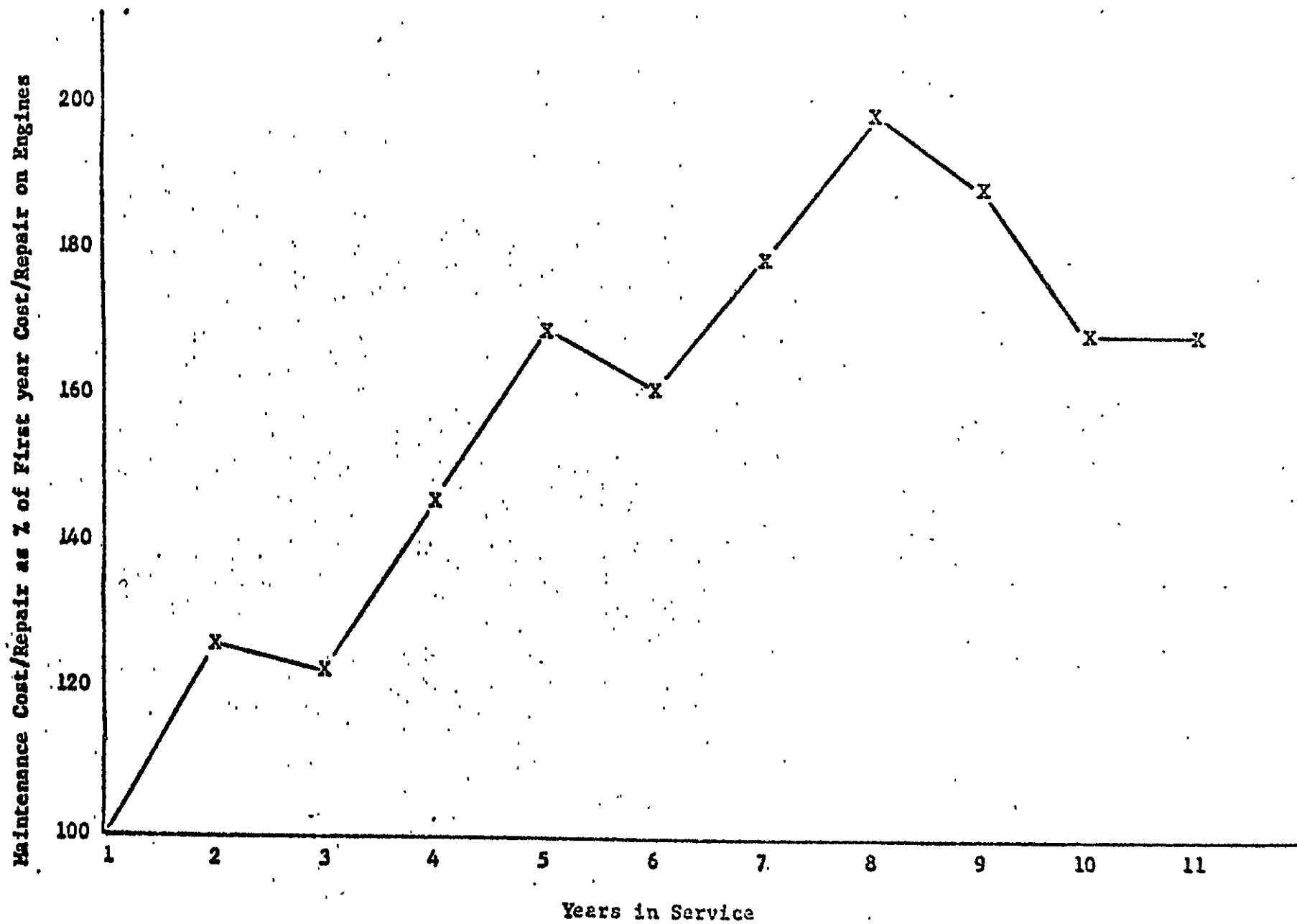
Figure 13.- Engine maintenance removal rates.



source: Sallee, op. cit. Figure II-3

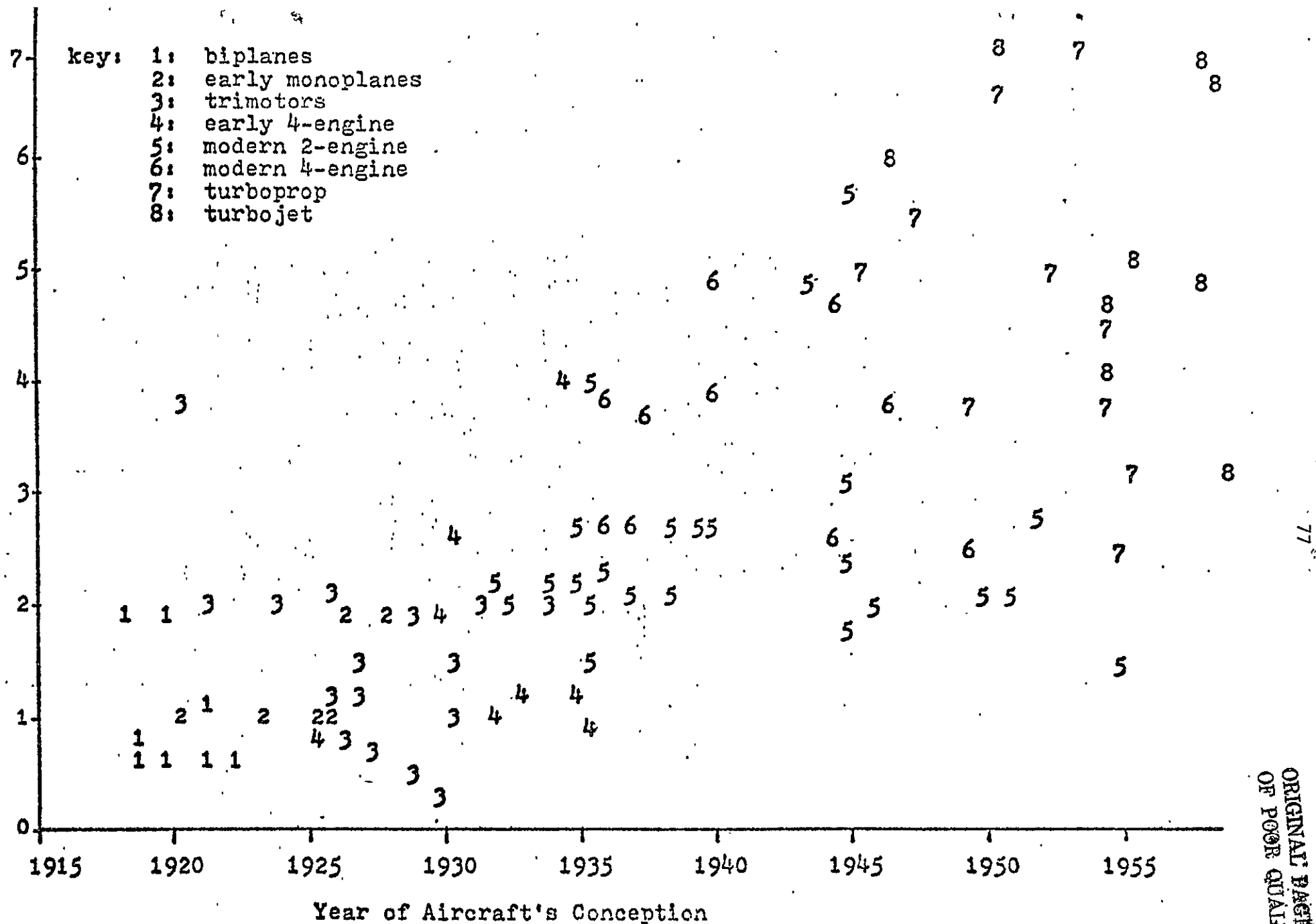
Figure 14.- Engine removal for overhaul and repairs vs time.





source: Sallee, op. cit. Figure II-4

Figure 15.- Relative total engine maintenance cost per repair.



Source: Brooks, op. cit. pp. 45, 50, 53, 56, 60, 71, 88, 107, 108

Figure 16.- Time lapse from conception to first service.

Aircraft Type	Maneuver	Subsonic Transport and Cruise	Supersonic Cruise	Hypersonic	Launch Vehicles
Boundary-Layer Growth and Separation	X	X	X	X	X
Boundary-Layer Transition		X	X	X	
Turbulent Boundary Layers	X	X	X	X	X
Boundary Layer/Shock Interactions	X	X	X	X	X
Separated Flows	X			X	X
Viscous Cross Flow	X	X	X	X	X
Viscous Corner Flow	X				
Viscous Mixing Effects	X	X	X	X	X
Base Flow and Wake Dynamics	X	X	X	X	X
Base Recirculation				X	X
Base Drag				X	X
Skin Friction	X	X	X		
Roughness, Protuberance Drag	X	X	X	X	X
Pressure Fluctuation	X				X
Vortex Flows	X	X	X	X	X
Interference Flow Fields	X	X	X	X	X
Jet Plume Interference	X	X	X	X	X
Bluff Body Aerodynamics				X	X
Heat Transfer				X	X

source: Nicks, O. W. The National Transonic Facility statement before House of Representatives Committee on Science and Technology, Feb. 10, 1976, Figure 5

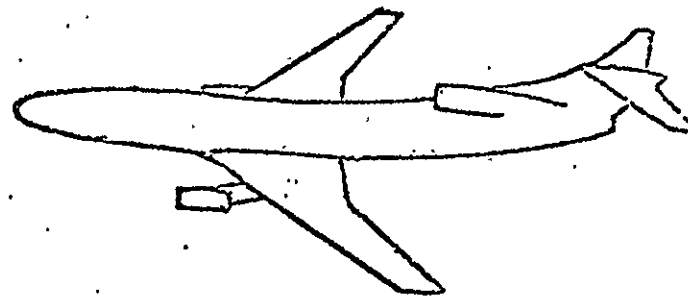
Figure 17.- Reynolds number sensitive phenomena for various types of aircraft.

## AERODYNAMIC ADVANCES

- ⊙ Supercritical airfoil
- ⊙ Configuration integration
- ⊙ Wing tip vortex diffusers

## POTENTIAL

- |                                |                            |
|--------------------------------|----------------------------|
| - Fuel conservation            | 1-1/2 Billion gallons/year |
| - Increased range/productivity | 20%                        |
| - Increased speed              | 15%                        |



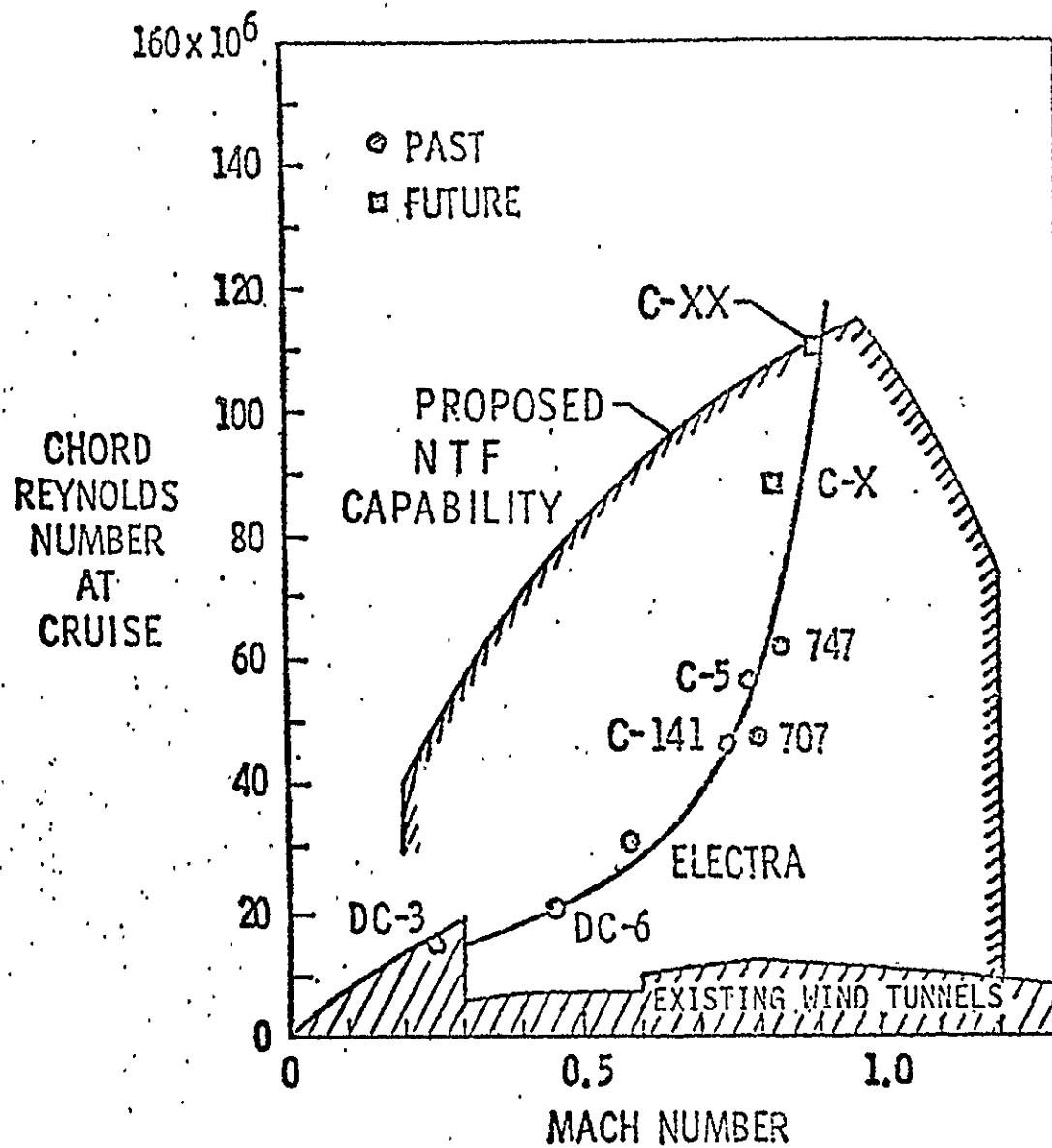
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TRANSONIC RESEARCH HOLDS THE KEY to competitive advanced civil transports, thousands of jobs, and multi-billion dollar commercial market.

source: Nicks, op. cit. Figure 8

Figure 18.- Effect of transonic research on the subsonic transport.

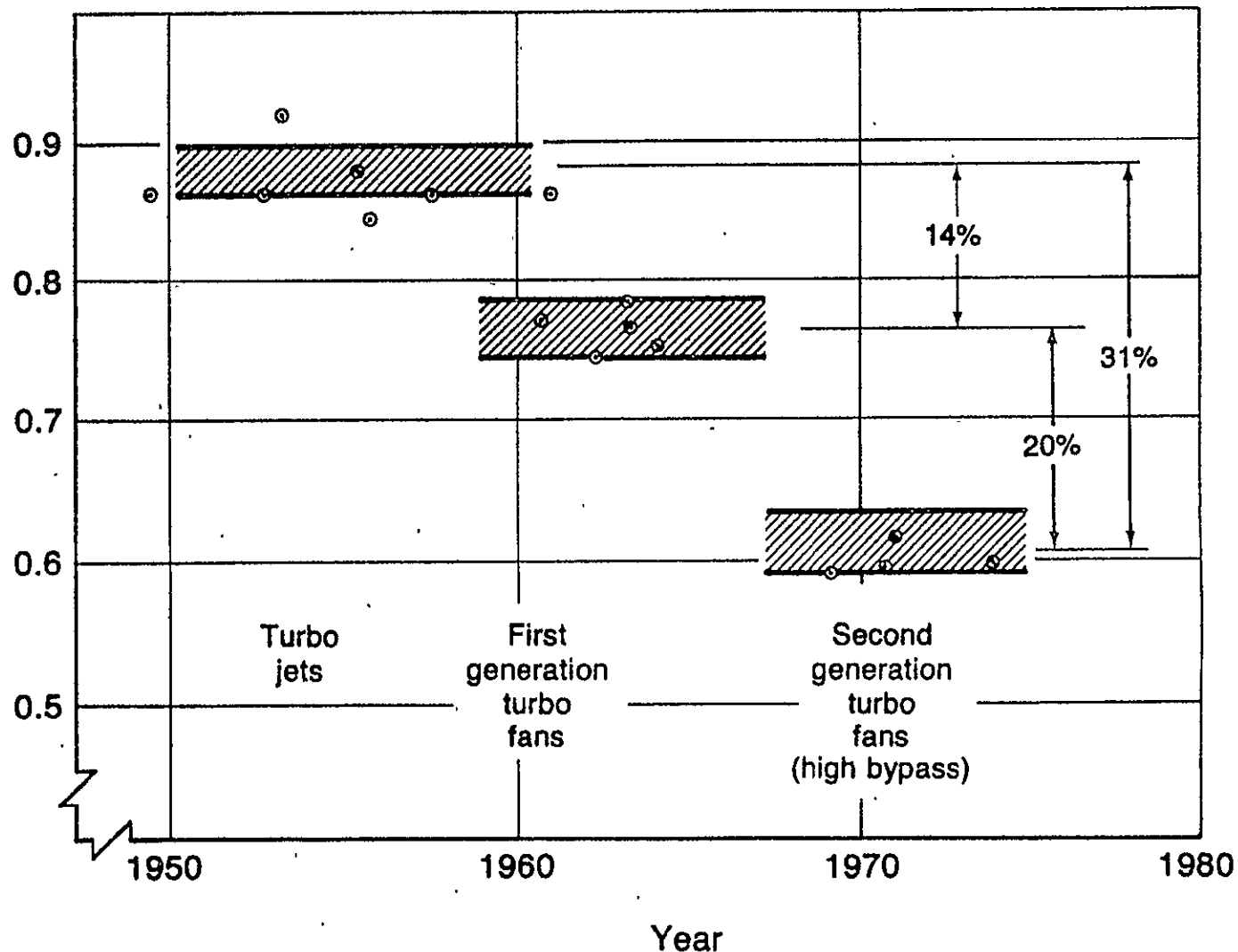
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source: Nicks, op. cit. Figure 7

Figure 19.- The growing Reynolds number gap.

Specific fuel  
consumption  
(lb of fuel  
consumed  
per hour per  
lb of thrust)



Source: Boeing Commercial Aircraft Company, op. cit. Figure 4

Figure 20.- Aircraft fuel efficiency trends.

Development Date	Date of Introduction								
	Pre-1945	1946-1948	1951-1953	1955-1957	1958-1960	1961-1962	1964-1967	1967-1969	Not Applied
Pre-1945	29	19	10	8	24	8	10		24
1945-1950		1	3	13	41	6	7		35
1951-1955				1	28	17	16	1	33
1956-1960					1	6	29	6	58
1961-1965							17	8	59
1966-1969							1	2	29

(a) Summary of aggregate advances.

Figure 21.- Time profile for utilization of technical advances in aircraft.

Development Date	Date of Introduction								
	Pre-1945	1946-1948	1951-1953	1955-1957	1958-1960	1961-1962	1964-1967	1967-1969	Not Applied
Pre-1945	15	2	1	2	11		2		7
1945-1950			2		6		3		11
1951-1955				1	3	3	4		18
1956-1960						1	2		13
1961-1965							5		17
1966-1969									7

(b) Utilization of advances in aerodynamics.

Figure 21 - Continued.



Development Date	Date of Introduction								
	Pre-1945	1946-1948	1951-1953	1955-1957	1958-1960	1961-1962	1964-1967	1967-1969	Not Applied
Pre-1945	5	4	1		6	2	2		11
1945-1950				2	12	3	1		12
1951-1955					10	8	4	1	8
1956-1960					1	1	4	1	17
1961-1965							1	3	18
1966-1969									10

(c) Utilization of advances in propulsion.

Figure 21.- Continued.

Development Date	Date of Introduction								
	Pra-1945	1946-1948	1951-1953	1955-1957	1958-1960	1961-1962	1964-1967	1967-1969	Not Applied
Pre-1945	1			1	1		3		
1945-1950		1		4	8		1		3
1951-1955					5	1	5		2
1956-1960							7	2	9
1961-1965							2	1	7
1966-1969									3

(d) Utilization of advances in structures.

Figure 21 - Continued.

Development Date	Date of Introduction								
	Pre-1945	1946-1948	1951-1953	1955-1957	1958-1960	1961-1962	1964-1967	1967-1969	Not Applied
Pre-1945		5	4	4	3	2	1		1
1945-1950				4	7	2	2		2
1951-1955					2	3			1
1956-1960						2	6	3	3
1961-1965							2	1	3
1966-1969									

(e) Utilization of advances in avionics.

Figure 21.- Continued.

Development Date	Date of Introduction								
	Pre-1945	1946-1948	1951-1953	1955-1957	1958-1960	1961-1962	1964-1967	1967-1969	Not Applied
Pre-1945	3				2				
1945-1950					2				
1951-1955					2		1		1
1956-1960							1		5
1961-1965							1		1
1966-1969								1	2

(f) Utilization of advances in flight mechanics.

Figure 21 - Continued.

Development Date	Date of Introduction								
	Pre-1945	1946-1948	1951-1953	1955-1957	1958-1960	1961-1962	1964-1967	1967-1969	Not Applied
Pre-1945	5	3	2			1			
1945-1950				2	1	1			1
1951-1955					2				2
1956-1960						2	3		3
1961-1965							5	1	2
1966-1969							1	1	5

(g) Utilization of advances in safety.

Figure 21.- Continued.

Development Date	Date of Introduction								
	Pre-1945	1946-1948	1951-1953	1955-1957	1958-1960	1961-1962	1964-1967	1967-1969	Not Applied
Pre-1945		4	1				1		2
1945-1950					3				1
1951-1955					4	1	2		1
1956-1960							3		5
1961-1965								2	5
1966-1969									

(h) Utilization of advances in human factors.

Figure 21 - Continued.

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Development Date	Date of Introduction								
	Pre-1945	1946-1948	1951-1953	1955-1957	1958-1960	1961-1962	1964-1967	1967-1969	Not Applied
Pre-1945		1	1	1	1				1
1945-1950			1	1	2				5
1951-1955						1			
1956-1960							1		3
1961-1965							1		6
1966-1969									2

(i) Utilization of other advances.

Figure 21.- Concluded.

<u>MATERIAL</u>	<u>BOEING USE</u>
NOMEX - nylon fiber (DuPont)	747 interior, e.g. ceiling & sidewall panels, stowage boxes, seat covers
LEXAN (General Electric)	747 interiors, e.g. passenger service unit, speaker panels, window reveals
PRD49 - fiber (DuPont)	Fiber reinforced helicopter blades
TEDLAR - hard, impervious film (DuPont)	747/707 interiors, e.g. 707 vinyl coating, 747 sidewall panel coating

Source: Boeing Commercial Aircraft Company, op. cit. Figure 16

Figure 22.- Examples of materials used by Boeing but developed elsewhere.



<u>ITEM</u>	<u>BOEING USE</u>	<u>OTHER APPLICATIONS</u>
o Structural Failure Sensing/ Warning Device	Failure detection for helicopter transmissions	Inexpensive and reliable detection for many types of oil-lubricated mechanical equipment
o Teflon Coating Process Boeclad	To coat metal jigs to prevent adhesives from sticking	Coating for stainless steel cookware to provide scratch-resistant, long wearing surface
o Roto-Scanner	Test straight, countersunk, and taper-shank fastener holes to detect hidden cracks	Same - in any structural member
o Flip-Lok Bushing	As permanently retained bushings	Same - auto industry
o Aero-Caster	Technology from air cushion vehicle work	Air bearing transporters for movement of almost anything. Currently used in aircraft industry, auto industry. Could even move buildings.
o Molalloy solid lubricant	Bearings, seals, gears, clutch facings, electric motor bushing, etc.	Same in other industries
o Beta Scope	Quality control measuring of thin films	Same in other industries

Source: Boeing Commerical Aircraft Company, op. cit. Figure 17

Figure 23.- Boeing invention disclosures developed for non-aircraft applications.

## APPENDIX A

Productivity

Productivity in the air transport industry is considered to be the amount of work an airplane can do for the operator in a given time and hence it is a measure of the revenue generating potential of the aircraft and can be expressed as ton-miles per hour<sup>1</sup> or passenger miles per hour<sup>2</sup>. Productivity when examined from the operator's viewpoint<sup>3</sup> includes considerations of the aircraft utilization (hours flown per year), passenger load factor and service life, in addition to number of seats and the cruising speed, but in this paper we will use  $(AS \times Vc)$  as a direct measure of productivity.

Revenue generating potential can also be increased by reducing operating costs. When the costs are reduced to such an extent that the return to the airline exceeds a fixed percentage (return on investment greater than average 12-15%) then the fare for the user can be reduced. This fare reduction can lead to an expansion in the market and a requirement for more aircraft (of the same or advanced type), providing the machines on hand are utilized to their fullest extent (i.e., operated at highest desirable load factor). In addition to consideration of  $AS \times Vc$  as an index of productivity, we will examine and discuss the changes in Direct Operating Costs per aircraft seat mile (DOC). In all considerations of productivity, and DOC, it must be remembered that the operation must show a profit or be subsidized to continue operations.

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<sup>1</sup>Stratford, Alan H., Air Transport Economics in the Supersonic Era, MacMillan & Co./St. Martins Press, N.Y., 1967, fig. 2.1, p. 40.

<sup>2</sup>Black, Richard H., and Stern, John A., Advanced Subsonic Transports - A Challenge for the 1990's. Douglas Aircraft paper 6336, AIAA Paper #75-304 (see fig. 5 and discussion).

<sup>3</sup>Glasgow, Charles S., Improving Aircraft Productivity - We all Have Part of the Action, Douglas Paper 6219, presented to the Air Transport Association of America. Engineering and Maintenance Conference, Key Biscayne, Miami, Florida, Oct. 10-12, 1973.

## APPENDIX B

## TOTAL PRODUCTIVITY IMPROVEMENT OF AIR TRANSPORT INDUSTRY

The attached Figures, A-I and A-II show quantitatively what the overall increased labor productivity has been in civil air transport and a calculation of what the significance of this has been in terms of social saving.

Additional information which underscores the productivity growth of the airlines over the period is demonstrated by the decrease in the cost to the users per passenger mile, from \$.34 in 1940 to about \$.06 in 1974, all in 1975 dollars. This is an average of about 5% per annum reduction in the revenue collected from the user per passenger. Corresponding to this reduced user cost is the increased demand for airline services, rising from around 10 billion revenue passenger miles in 1950 to about 350 billion in 1974, representing a 16% per annum increase, as shown in Figures A-III and A-IV.<sup>1</sup>

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<sup>1</sup>Boeing Commercial Airplane Company, op. cit., p. 4 and Figures 8 and 9.

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Year	Output <sup>2</sup>	Labor Force	Output/ Unit Labor
1929	0.5	2.3	22.6
1930	1.3	3.5	37.1
1931	1.5	5.5	27.3
1932	1.3	6.8	26.5
1933	2.4	7.2	33.3
1934	2.8	7.7	36.4
1935	4.6	8.9	51.7
1936	6.3	11.0	57.3
1937	7.1	13.0	54.6
1938	8.0	15.0	53.3
1939	10.6	17.6	60.2
1940	15.2	22.9	66.4
1941	20.4	29.3	69.6
1942	24.7	41.0	60.2
1943	31.7	55.4	57.2
1944	42.6	56.6	75.3
1945	60.9	63.9	95.3
1946	87.1	98.8	88.2
1947	100.0	100.0	100.0
1948	104.5	96.4	108.4
1949	117.3	95.2	123.2
1950	136.0	95.2	142.9
1951	171.2	108.4	157.9
1952	199.4	124.1	160.7
1953	228.5	132.5	172.5

1- The Indices have been normalised to base year of 1947

2- Output is proportional to "revenue passenger miles"

source: Kendrick, op. cit. p. 555

Figure A-I.- Historical indices of airline transport labor productivity.

(All prices 1954)

1964 traffic levels  $106.316 \times 10^9$  available seat miles flown

Operating costs/seat mile

1933 \$ .078

1964 \$ .016

Cost of 1933 technology in 1964 =  $\$ 8.293 \times 10^9$

Cost of 1964 " " " =  $\$ 1.701 \times 10^9$

Airline Expenses, 1964 =  $\$ 3.275 \times 10^9$

Social Savings =  $(8.293 \times 10^9 - 1.701 \times 10^9) = \$6.592 \times 10^9$

% Social Saving =  $\frac{6.592}{8.293} = 80.3\%$

Social Saving as % of Airline expenses:  $\frac{6.592}{3.275} = 200\%$

1964 expenses using 1933 a/c tech =  $(\$3.275 + \$6.592) \times 10^9 = \$9.867 \times 10^9$

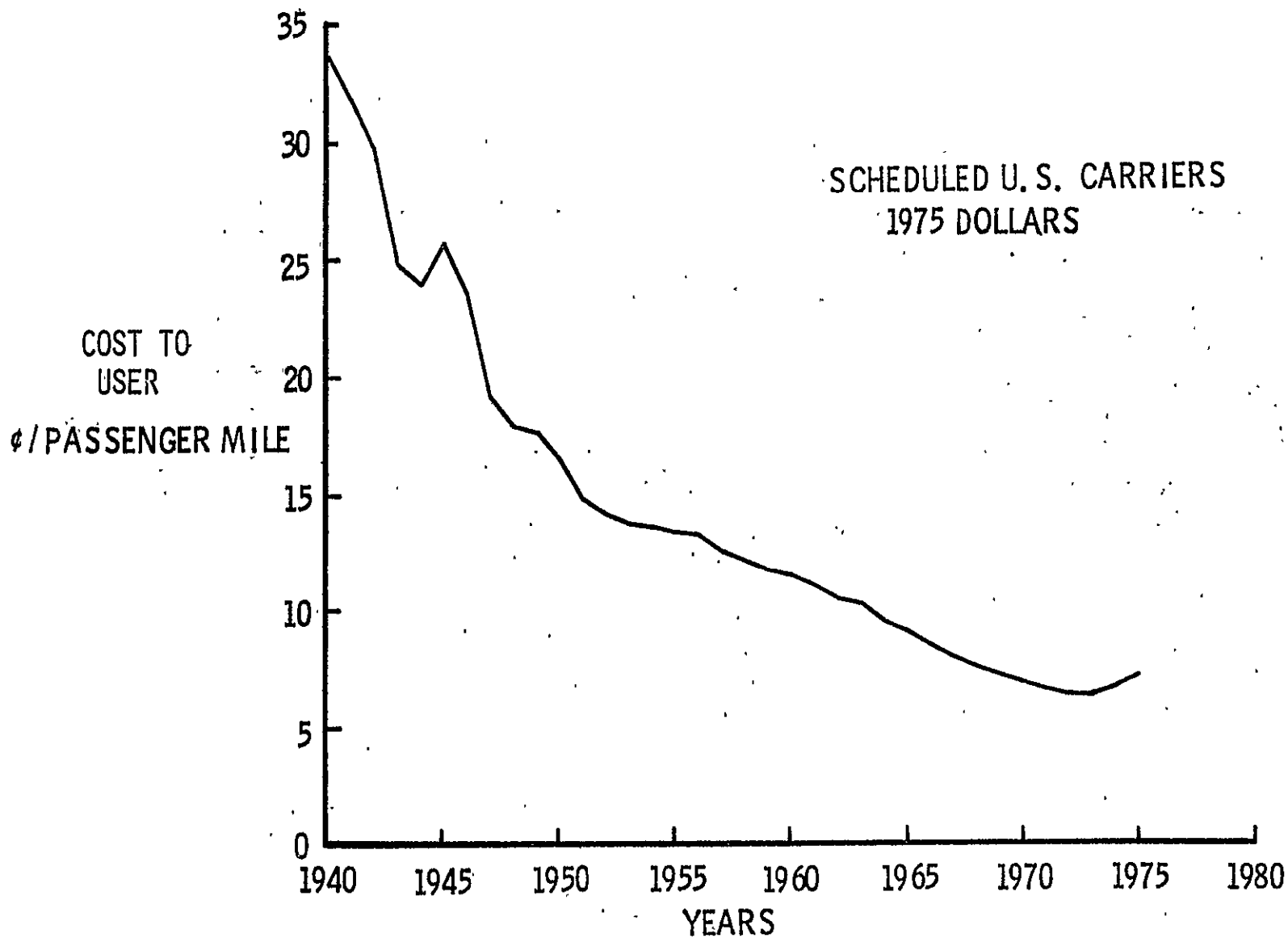
% reduction due to tech advance =  $6.592/9.867 = 66.9\%$

Source: Handbook of Airline Statistics, CAB, Washington, D. C. 1973 edition.

Table 14, p. 22, col. 2, Total Certificated route, air carriers

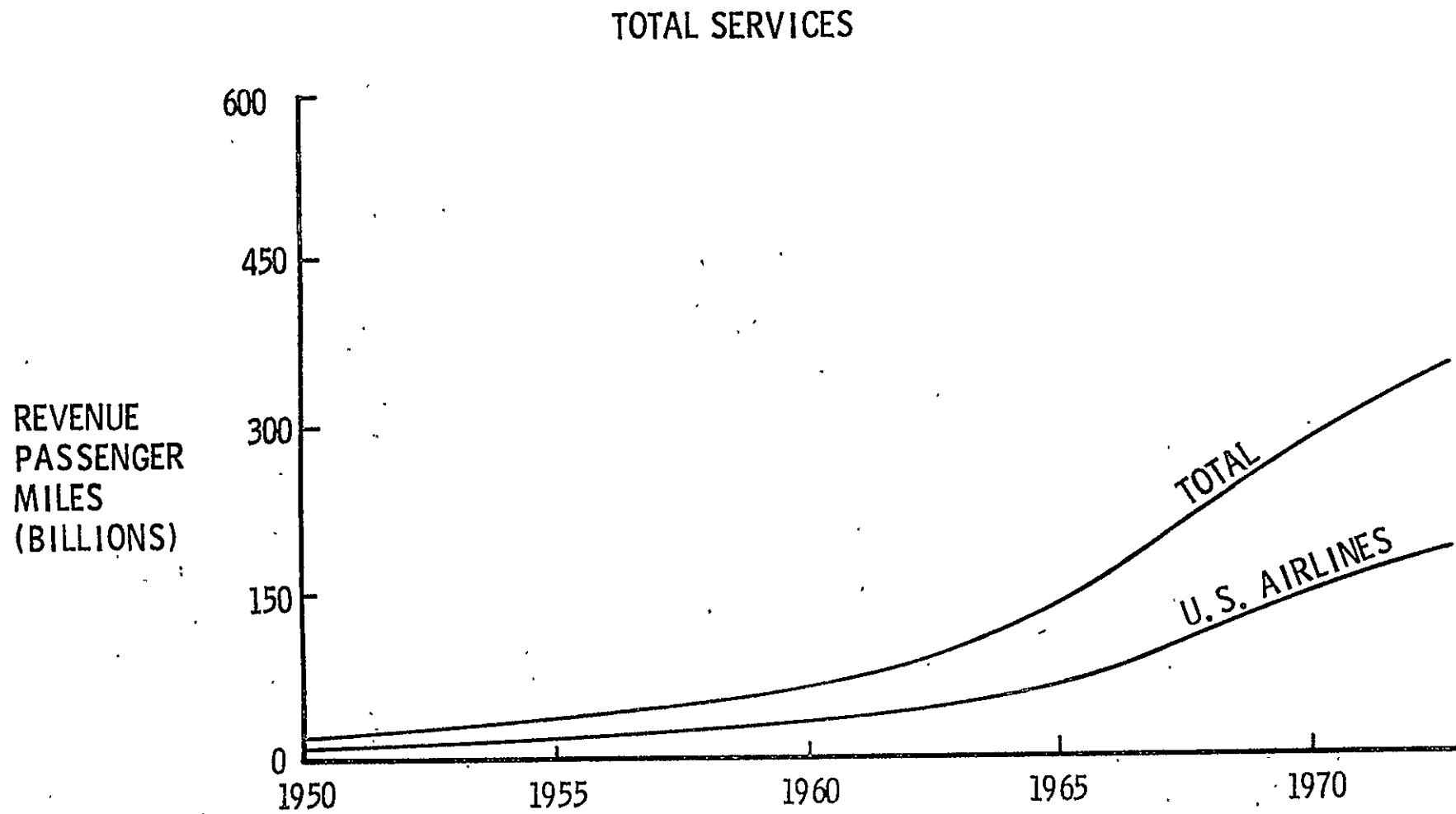
Figure A-II.- Calculation of social saving.

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Source: Boeing Commercial Aircraft Company, op. cit. Figure 8.

Figure A-III.— Revenue per passenger mile.



Source: Boeing Commercial Aircraft Company, op. cit. Figure 9

Figure A-IV.— Growth of revenue passenger miles.